Radiazione di Alta Energia nell'Universo

Energia > 100 MeV (10^8 eV)

Energia (massima) = 10^{21} eV
(forse ancora maggiore)

Raggi Cosmici

Fotoni

Neutrini

Luce Visibile:

λ_{max} = 2900/T μmK   1eV == 1.24 μm

Rosso λ = 6800 Å E = 1.82 eV T = 4264 K

Giallo λ = 5850 Å E = 2.11 eV T = 4957 K

Verde λ = 5550 Å E = 2.33 eV T = 5225 K

Blu λ = 4350 Å E = 2.85 eV T = 6666 K

10^3 eV KeV

10^6 eV MeV

10^9 eV GeV

10^{12} eV TeV

10^{15} eV PeV

10^{18} eV EeV

10^{21} eV ZeV

Studio dei Processi piu' "Violenti" nell'Universo

La maggior Parte degli oggetti del Cosmo sono
in buona approssimazione in **EQUILIBRIO TERMICO**

Ex: Stelle emettono Radiazione di Corpo Nero
[Sole : $T_{surface} \cong 5780$ Kelvin $\cong$ 2 eV]

Ex: Sorgenti a Raggi X
[$T \cong$ KeV]

Ex: Proto-Neutron Star (Supernova Explosion)
[$T \cong$ MeV]

Processi Dinamici **NON TERMICI**

SORGENTI:

SUPERNOVA REMNANTS

PULSARS

ACTIVE GALACTIC NUCLEI

GAMMA RAY BURSTS

....

COSMIC RAYS

Discovery

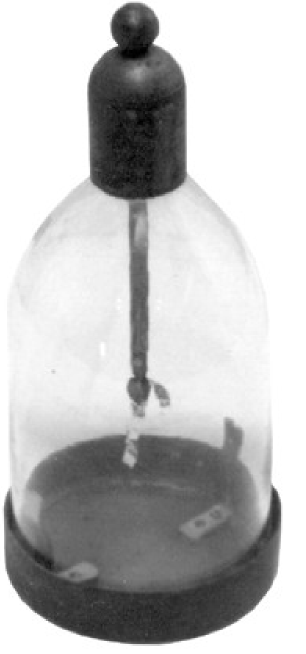
Structure of the Energy Spectrum

Magnetic Confinement in the Galaxy

Geomagnetic Effects

Solar Modulation

Discovery of Cosmic Rays



1st Observations at the beginning of 1900
Discharge of electroscopes → Existence of IONIZING RADIATION

1912 Victor Hess (and others) establish with measurements with Ionization Chambers on balloons that the radiation is coming from outside the Earth. Ionization initially decreases with altitude, then increases.

1912 Domenico Pacini establish with measurements with ionization chambers under water that the radiation is coming from above. Ionization decreases with increasing depth.

Victor Hess

before the balloon fligh of 1912

V. Hess, Ueber Beobachtung der durchdringenden Strahlung bei Sieben Freiballonfahrten, Phys. Zeitsch. 13, (1912) 1084 (Nobel prize 1936).

Also A. Goekel, Messung der durchdringenden Strahlung bei Ballonfahrten, Phys. Zeitsch. (1911) 595

Discovery of Cosmic Rays
Beginning of
High Energy Astrophysics

Domenico Pacini

1912

Ionization decreases 3m under water compared to surface

D. Pacini, La radiazione penetrante alla superfice ed in seno alle acque, Nuovo Cimento VI/3 (1912) 93

First underwater experiment

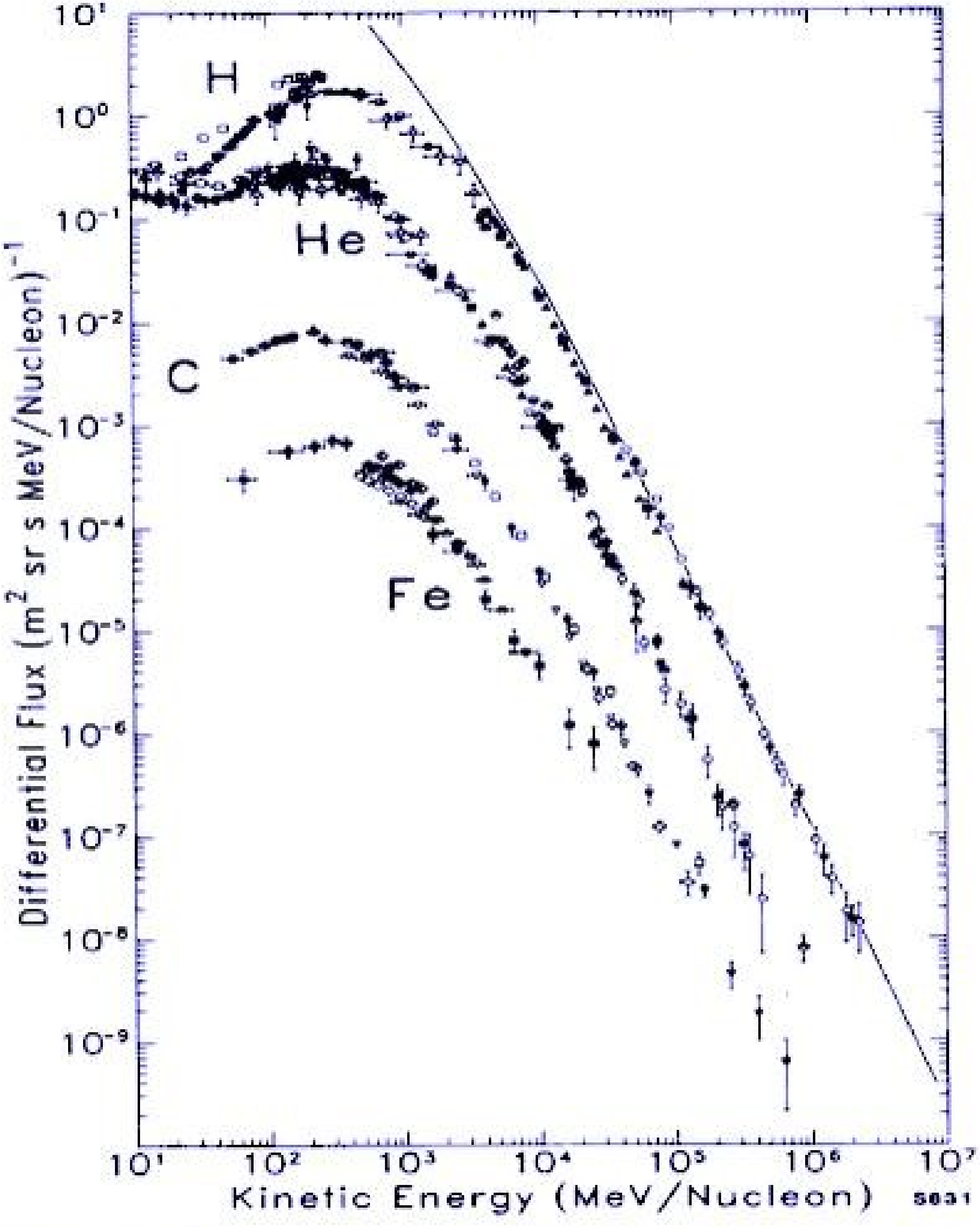


Figure 2. The differential energy spectra of the primary cosmic ray H, He, C, and Fe at Earth. [*Reproduced with permission from J. A. Simpson (1983)*. Ann. Rev. Nucl. Part. Sci. **33** *by Annual Reviews, Inc.*].

Power-Law
Energy Spectrum
spectra

$$\phi(E) \simeq K\ E^{-\alpha}$$

$$\alpha \simeq 2.7$$

FLUSSO di particelle

Numero di Particelle per
[Unita' di Superficie
Unita' di tempo
Unita' di Angolo Solido
Unita' di Energia]

Dimensioni :

[Superficie Tempo Angolo-solido Energia]$^{-1}$

Unita' di Misura :

$[cm^2 \ s \ sr \ GeV]^{-1}$

Flussi riportati come:

1) Particelle per GeV per nucleone
2) Particelle per unita' di Rigidità
3) Nucleoni per GeV per nucleone
4) Particelle per GeV

Rigidity = p/Ze

Per uno spettro $\phi(E) \simeq K\ E^{-\alpha}$

$\alpha = 1+\gamma$ (γ indice dello spettro integrale)

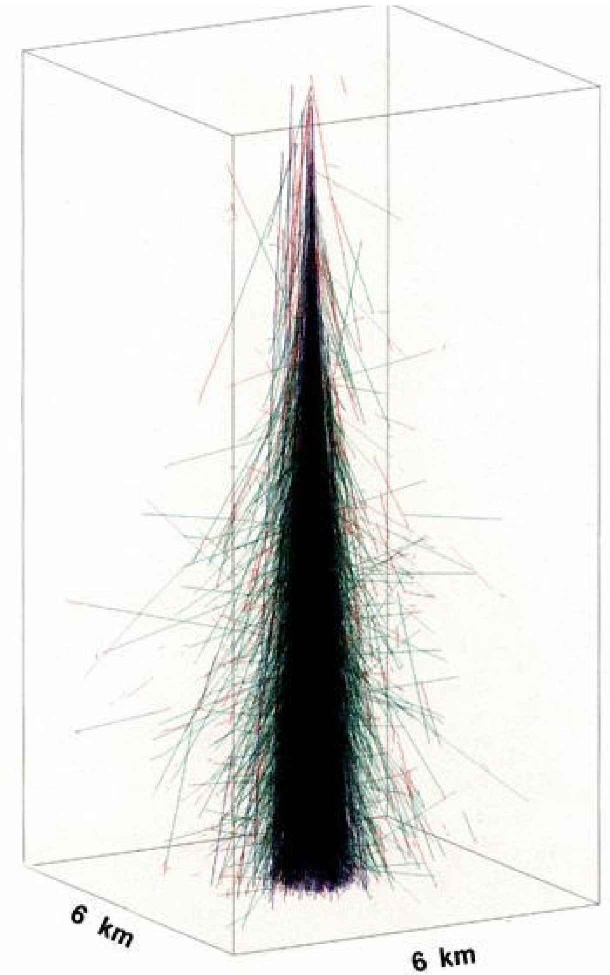
La frazione per

1) F_A
2) $2^{\gamma}F_A$
3) AF_A
4) $A^{\gamma}F_A$

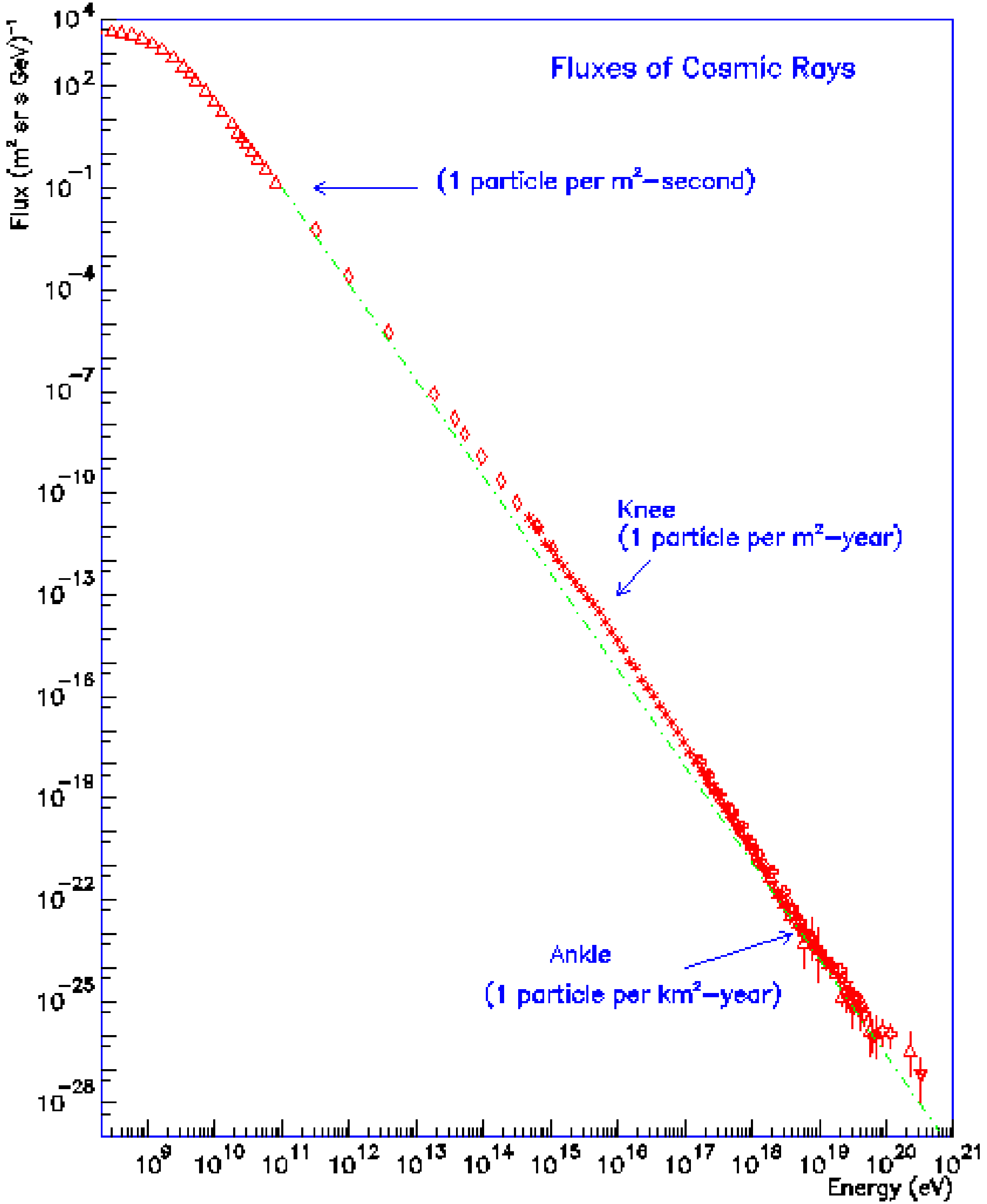
Table 1.1: Fraction of nuclei relative to protons.

Mass group	$< A >$	(1) Particles ($> E/A$)	(2) Particles ($> R$)	(3) Nucleons ($> E/A$)	(4) Particles ($> E$/nucleus)
p	1	1	1	1	1
α	4	0.036	0.12	0.14	0.38
M ($Z = 6$ to 9)	14	0.0025	0.0083	0.035	0.22
H ($Z = 10$ to 20)	24	0.0007	0.0023	0.017	0.15
VH ($Z = 21$ to 30)	56	0.0004	0.0013	0.022	0.40

$10^{-2.7} = 1 / 501$



$E = 10^{19}$ eV



FLUSSO integrale di particelle :

1 GeV 10000 /s/m^2
1 TeV 1 /s/m^2
10 PeV 3 /y/m^2
10 EeV 1 /y/km^2
100 EeV 1/100y/km^2

Proton, Nuclei Spectra

$$\phi(E) \simeq K\ E^{-\alpha} \qquad \alpha \simeq 2.7$$

KNEE (steepening of the Spectrum) α: $2.7 \to 3$

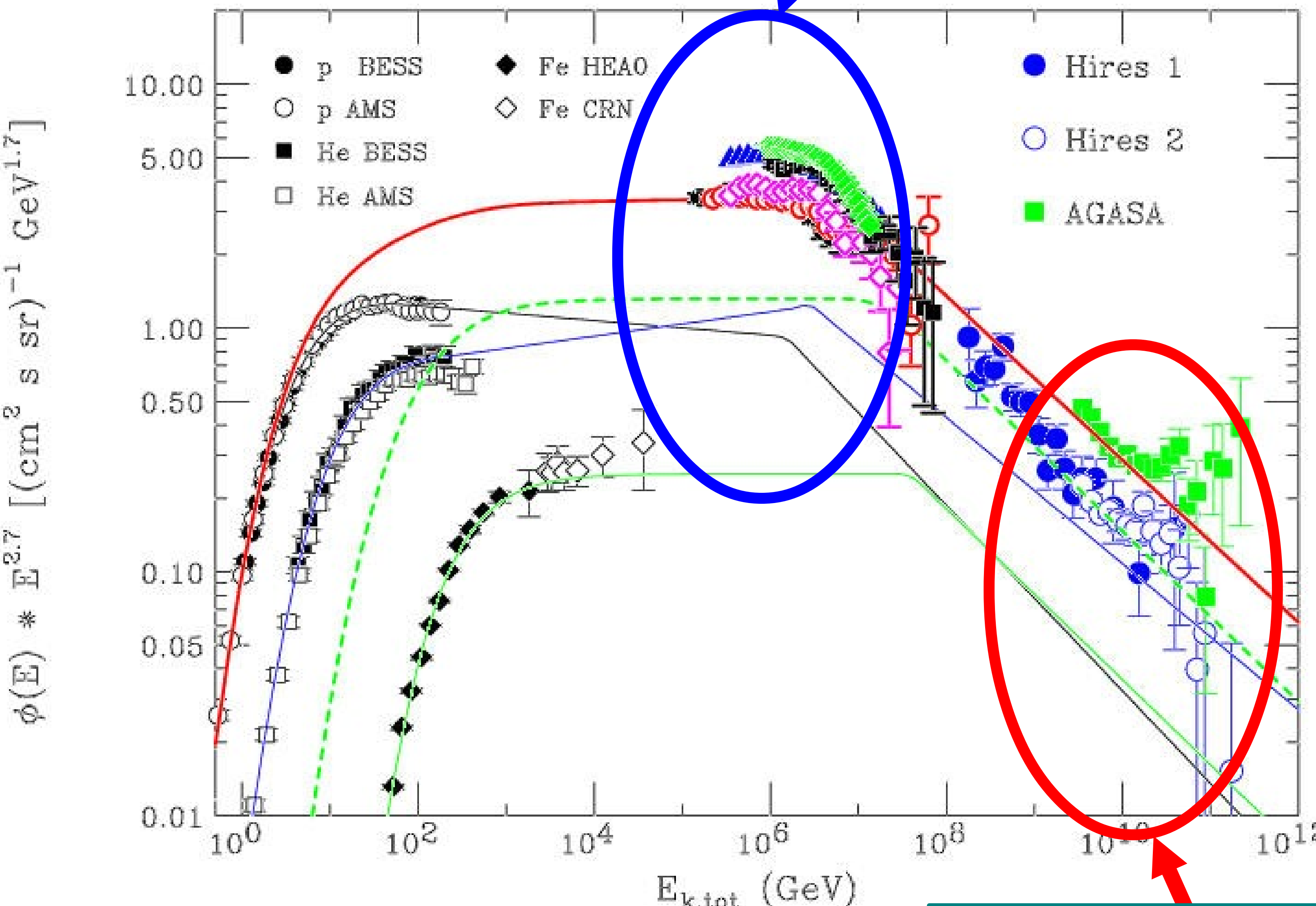
ANKLE (hardening of the spectrum) α: $3 \to 2$–2.7

$$E_{\rm Knee} \simeq 3 \times 10^{15}\ {\rm eV}$$

$$E_{\rm Ankle} \simeq 10^{19}\ {\rm eV}$$

Spectrum Multiplied by $\mathbf{E}^{2.7}$

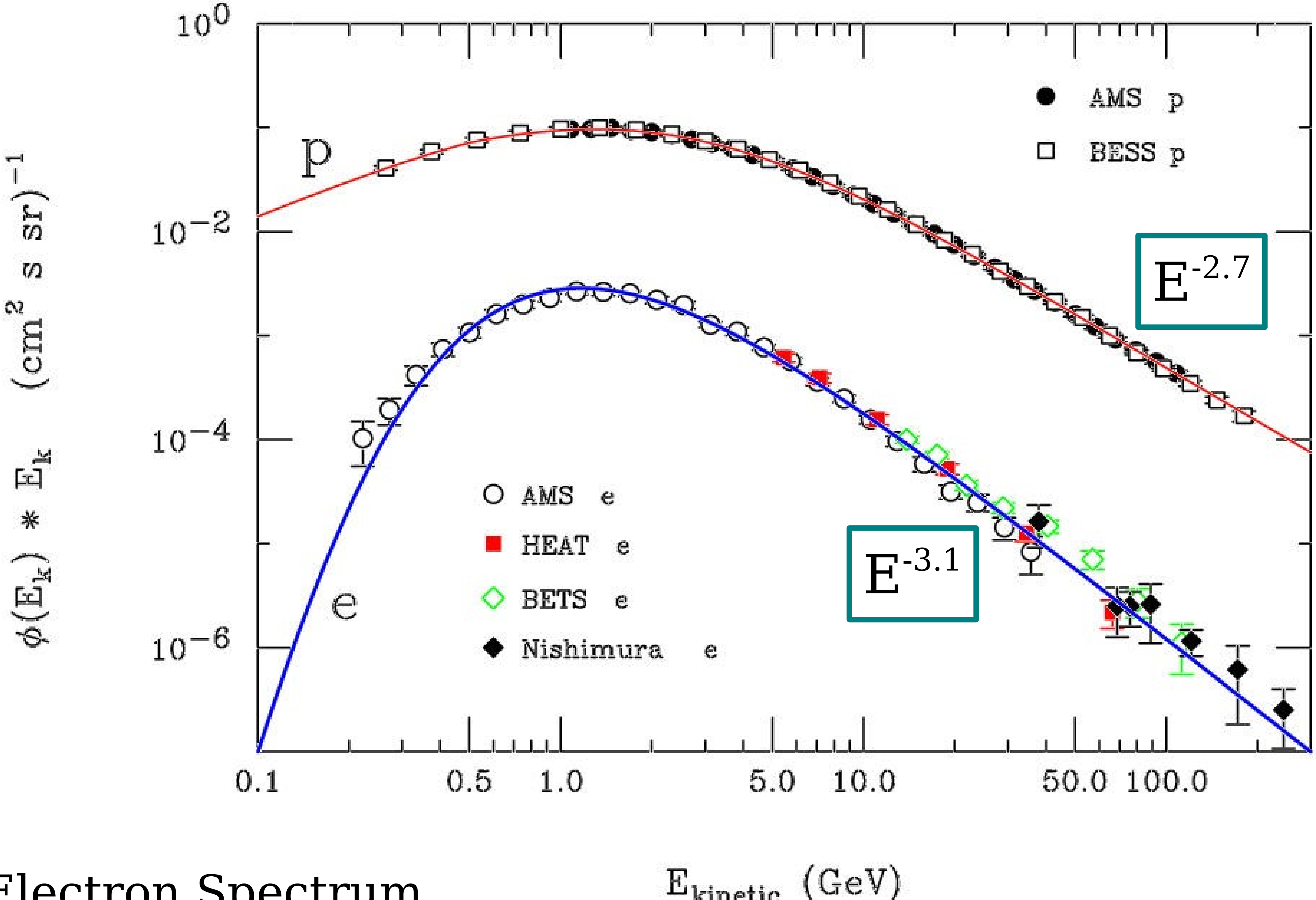
Knee Region



GZK Region

$$p + \gamma_{(2.7\,\mathrm{K})} \rightarrow p(n) + \pi + \ldots$$

Proton and **Electron** spectra at the Earth



Electron Spectrum
is "steeper" (softer)

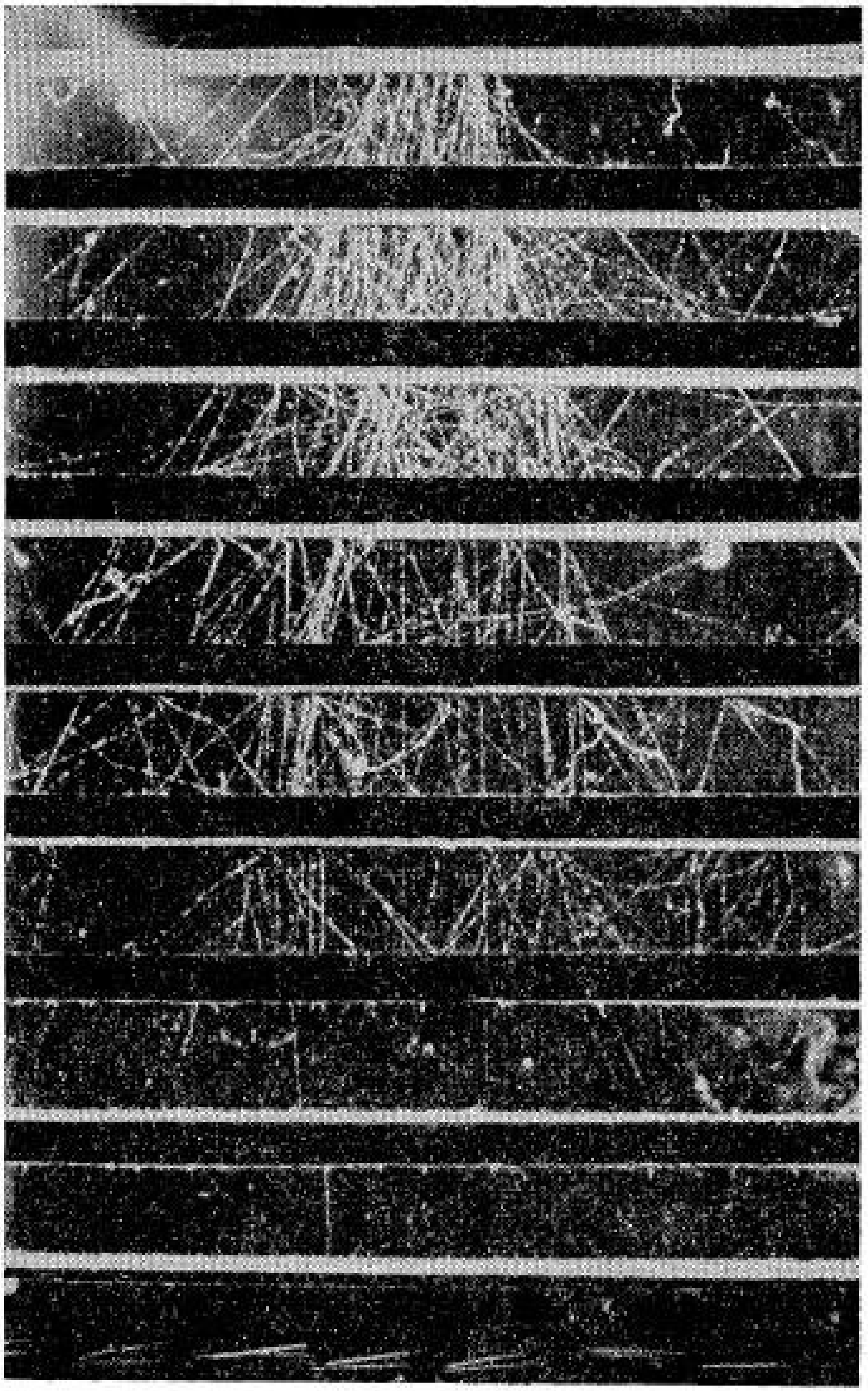
Understanding of the Nature of the
Cosmic Rays took a long time.

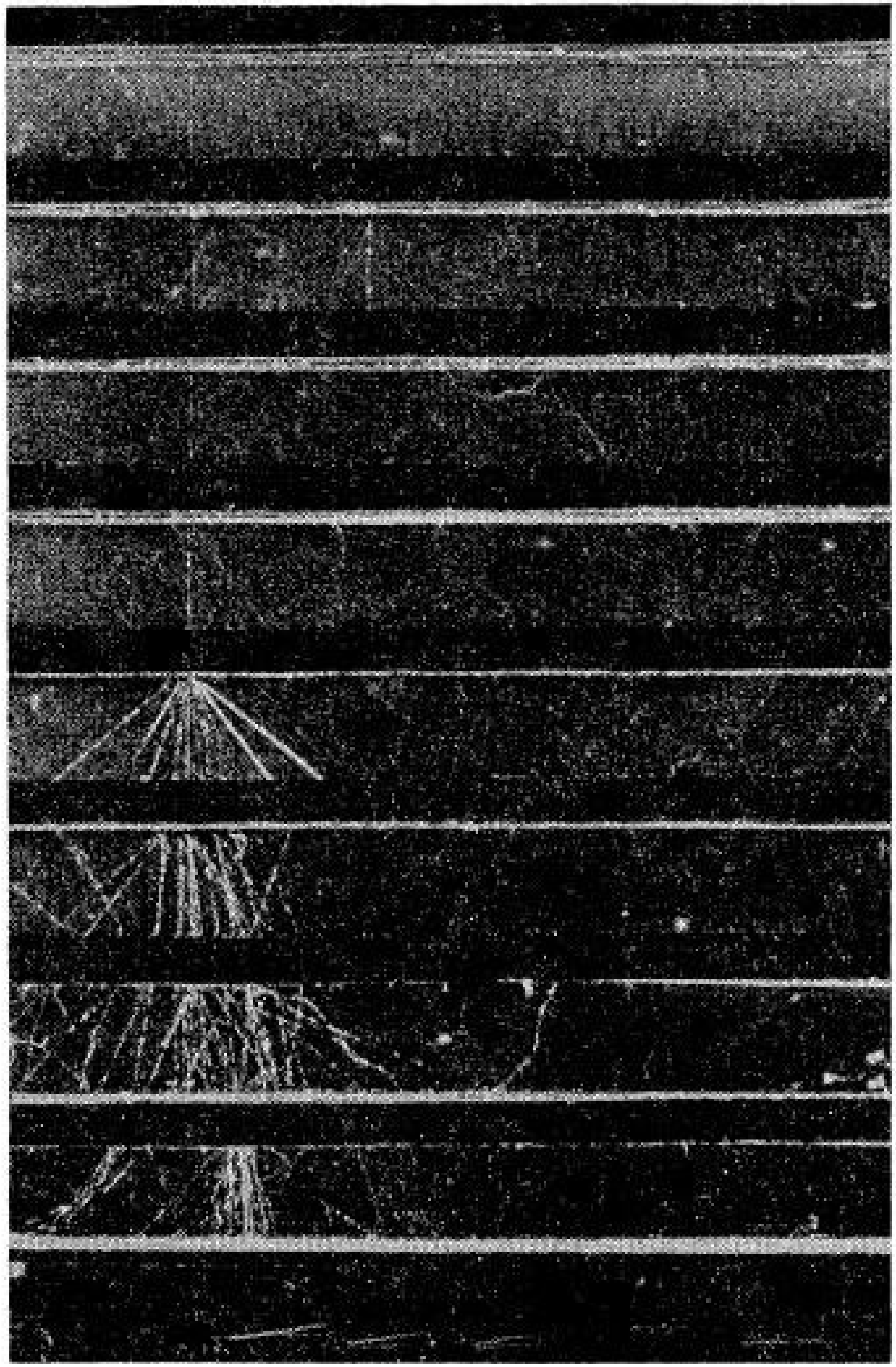
Particles observed at the Surface of the Earth
are SECONDARIES. Essentially all primary particles
interact at high altitudes (stratosphere h > 10 Km)
producing secondaries, that again interact ...

Photons
Electrons
Positrons

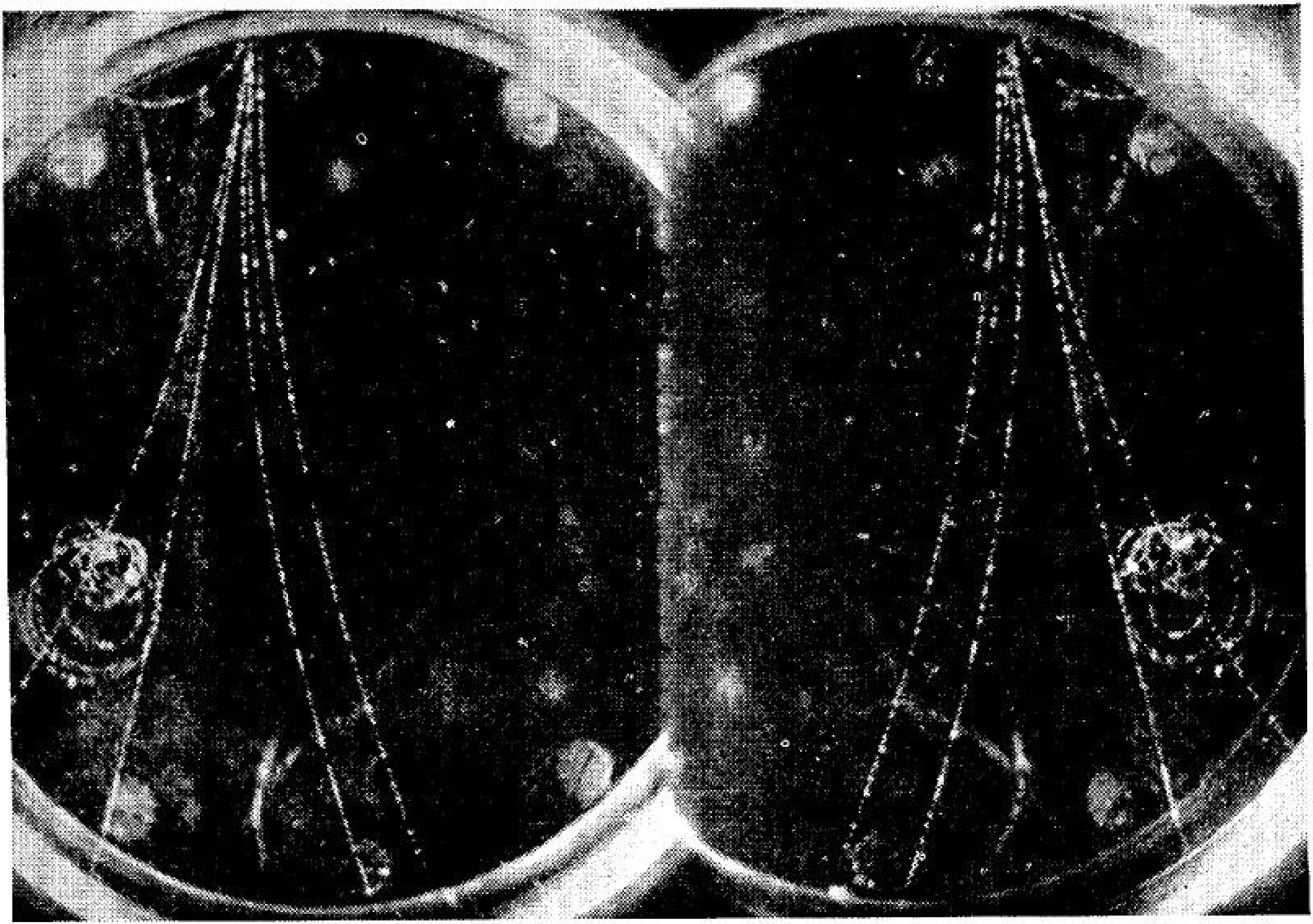
Muons

Hadrons:
- Protons
- neutrons
- Kaons ....





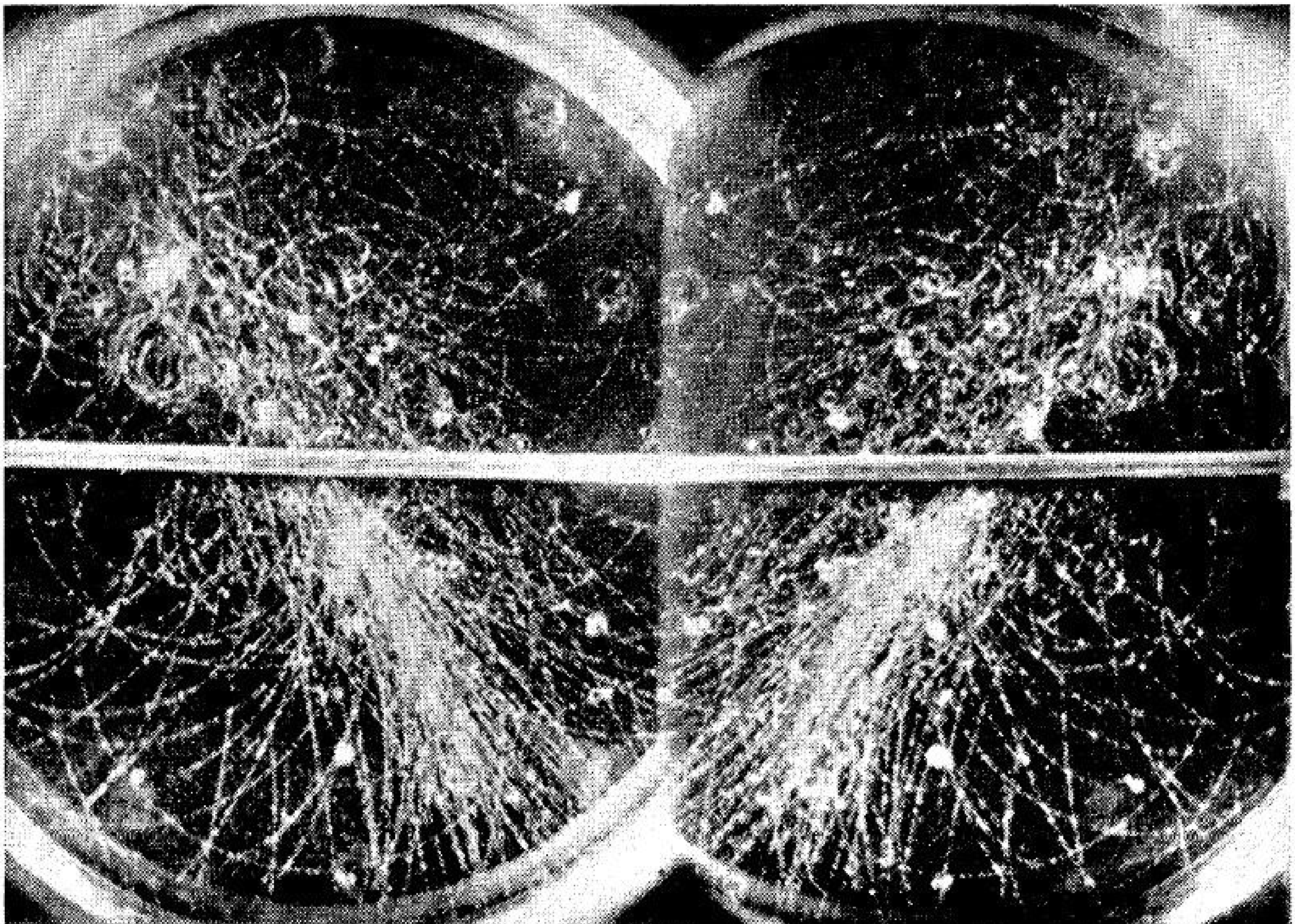
ELECTRONS and POSITRONS



Cloud Chamber Observations of Cosmic Rays at 4300 Meters Elevation and Near Sea-Level

CARL D. ANDERSON AND SETH H. NEDDERMEYER, *Norman Bridge Laboratory of Physics, California Institute of Technology*

(Received June 9, 1936)

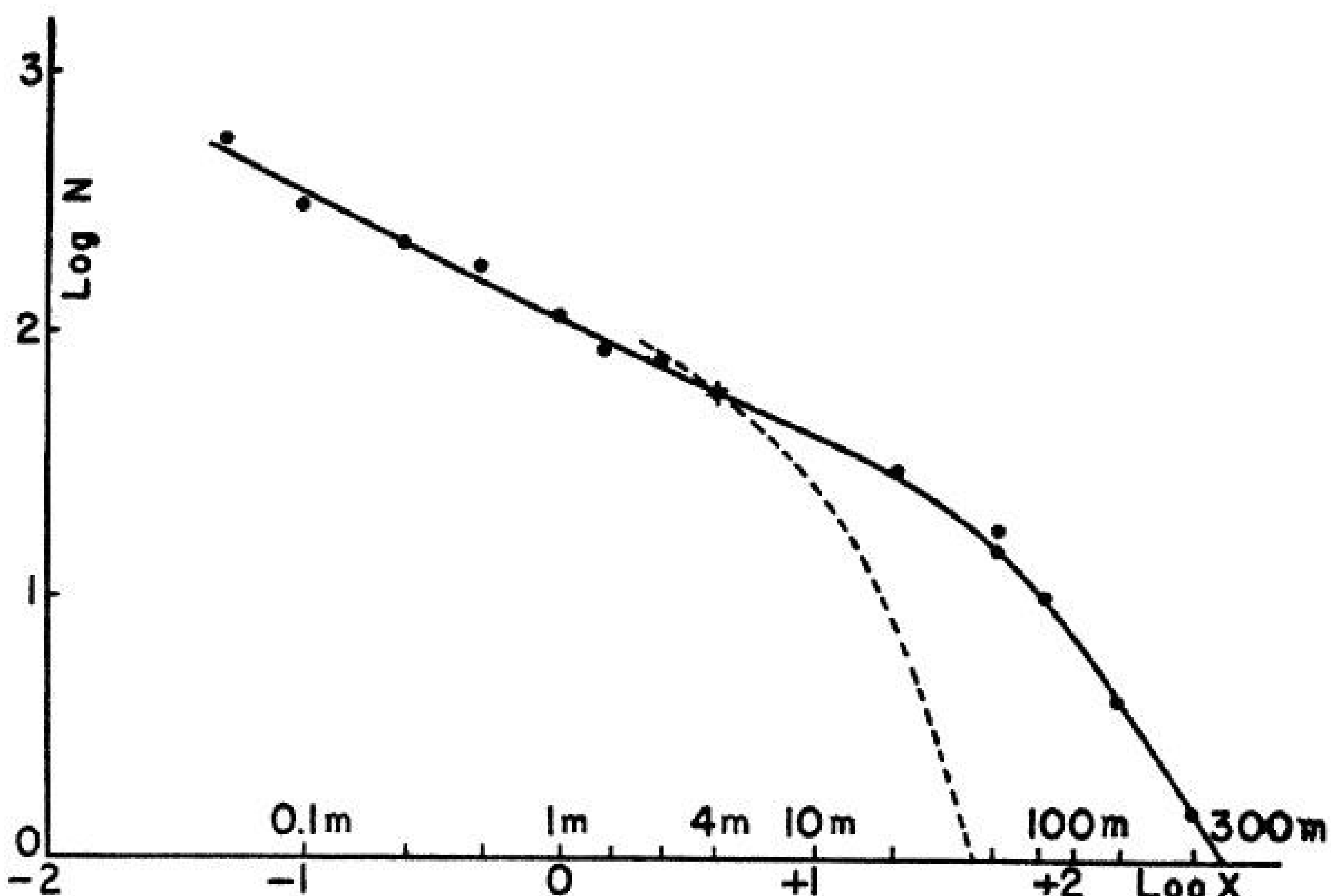


Pierre Auger

JULY–OCTOBER, 1939 REVIEWS OF MODERN PHYSICS

Extensive Cosmic-Ray Showers

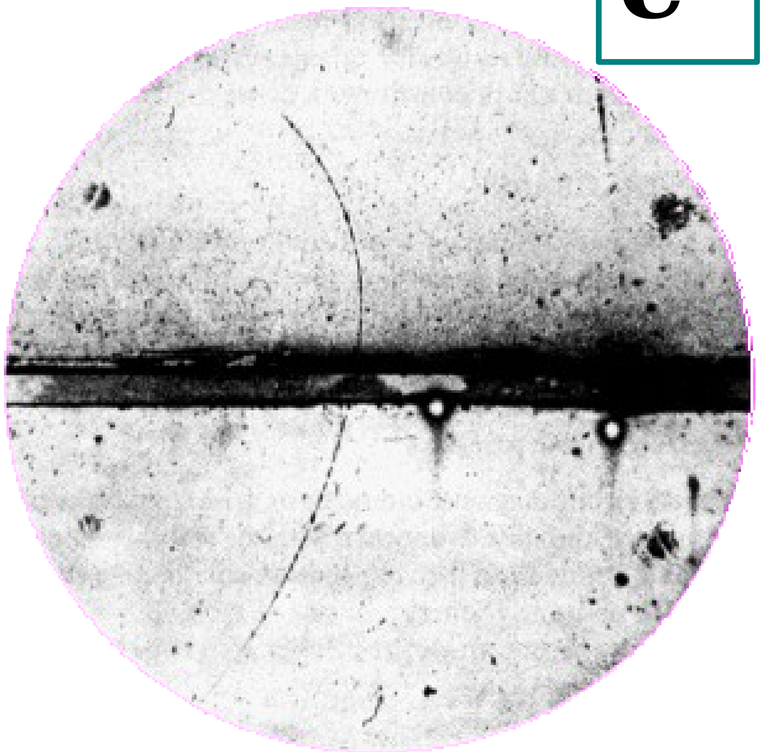
PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France



Extensive Air Showers

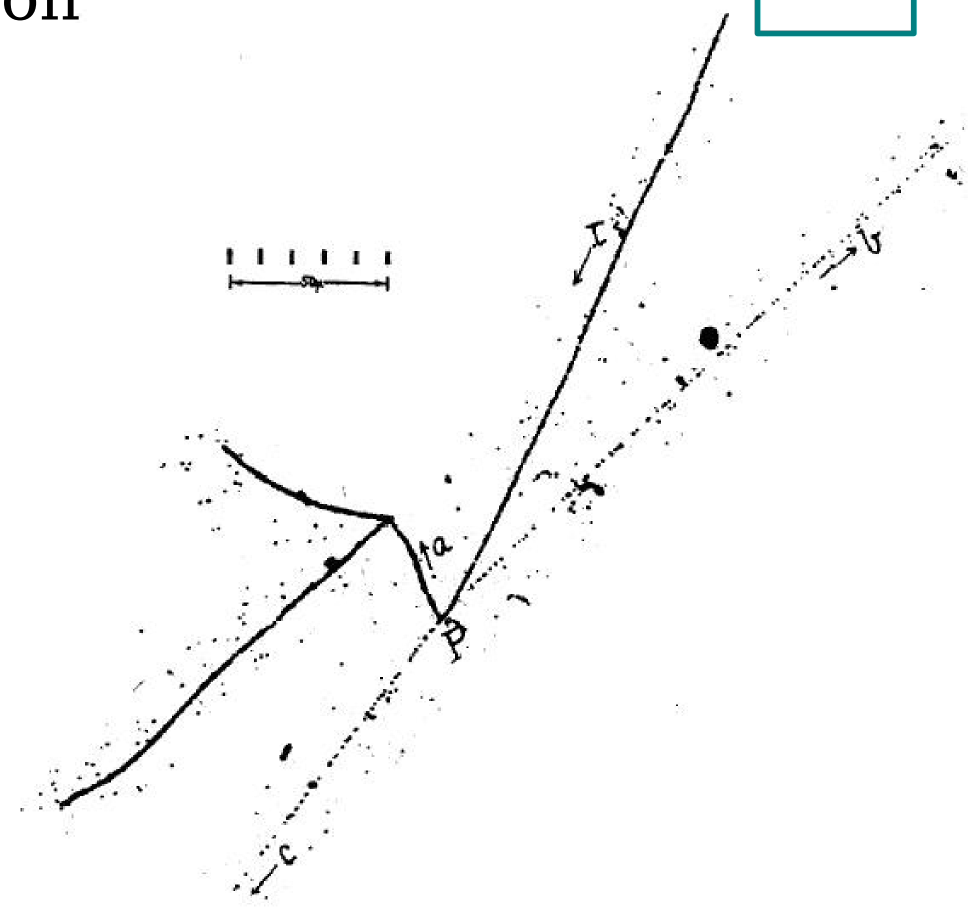
Particle Physics ← **Cosmic Ray Physics**

e^+

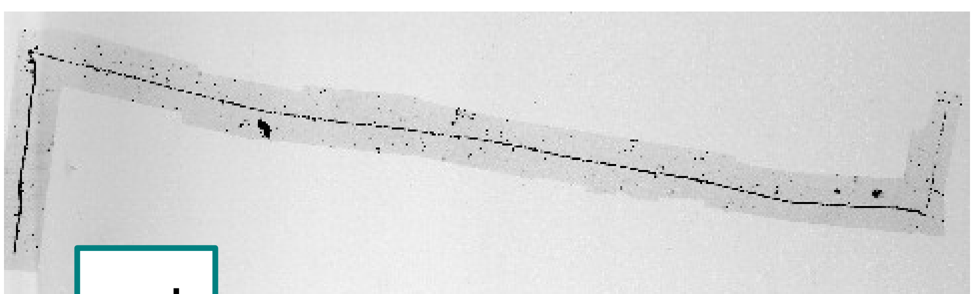


Anderson discovery of positron

$K^\pm$



$\pi^\pm$



GEOMAGNETIC EFFECTS

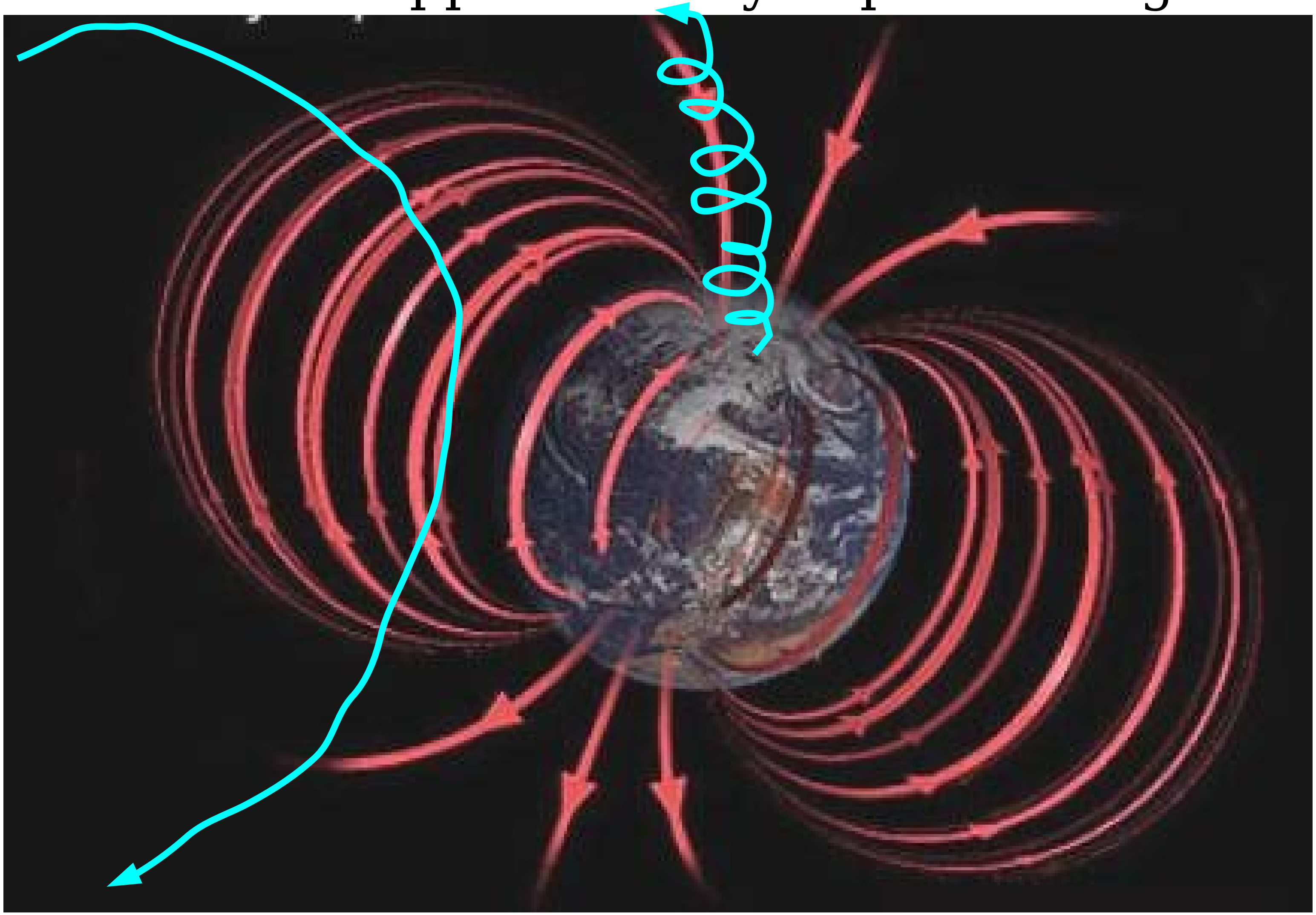
Effetto del campo magnetico terrestre
sui raggi cosmici

SOLAR MODULATIONS

Effetto del vento solare sui raggi cosmici

GEOMAGNETIC EFFECTS

Earth has an approximately dipolar magnetic field



Latitude Effect

At the magnetic pole particles of any rigidity can arrive
At the equator the geomagnetic effect is maximum

Cosmic Rays in **Interstellar Space** are

(1) Isotropic in Direction
(Directions randomized by the geomagnetic field)

(2) Constant in time
(Or better very slowly varying with time).

At the Earth the Cosmic Rays have
some small anisotropy and time variations
because of Solar and
Terrestrial (Geomagnetic) effects.

COMPTON (1933) Cosmic Rays are CHARGED

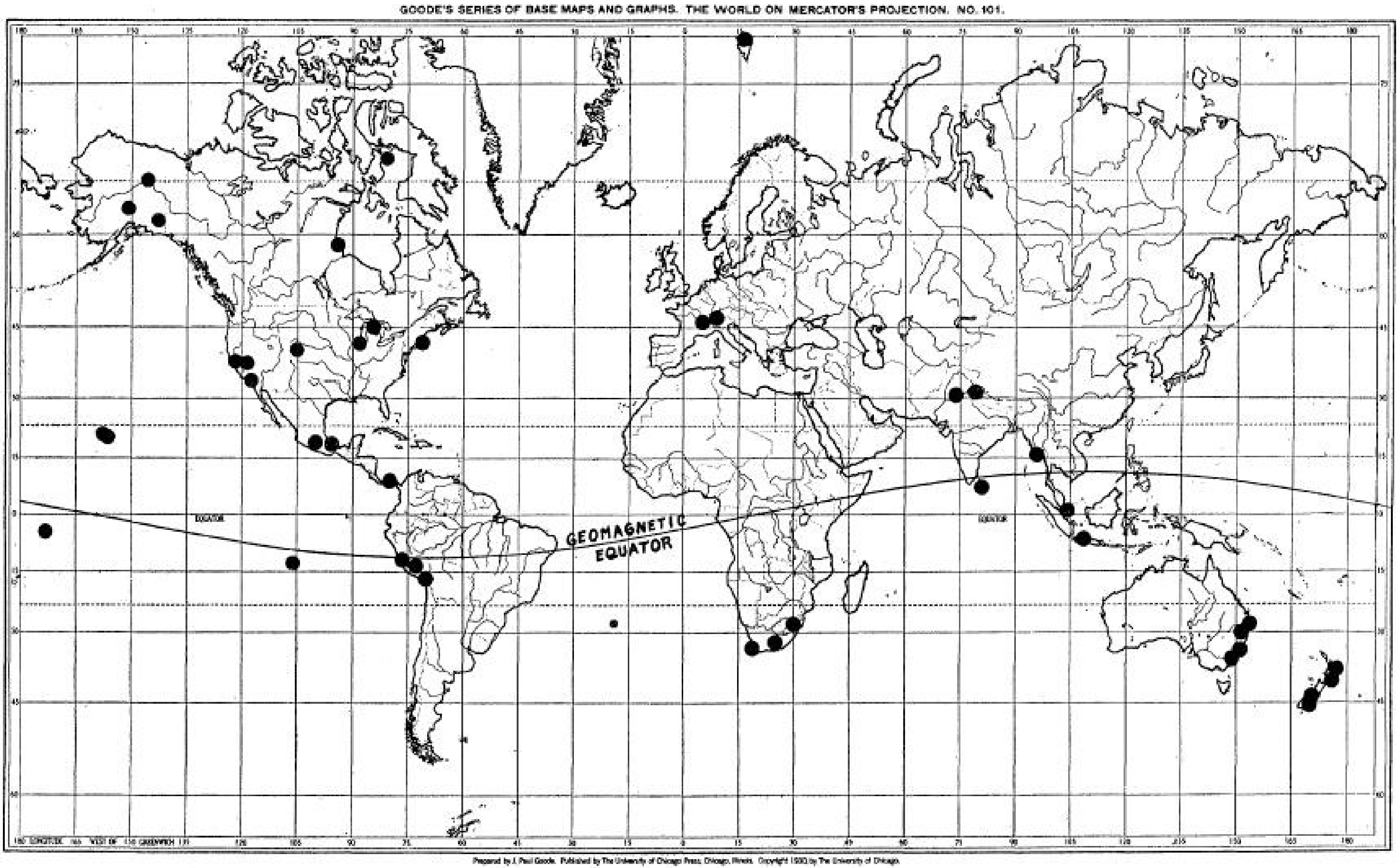


Fig. 1. Map showing location of our major stations for observing cosmic rays.

LATITUDE EFFECT

A Geographic Study of Cosmic Rays

ARTHUR H. COMPTON, *University of Chicago*

(Received January 30, 1933)

LATITUDE EFFECT

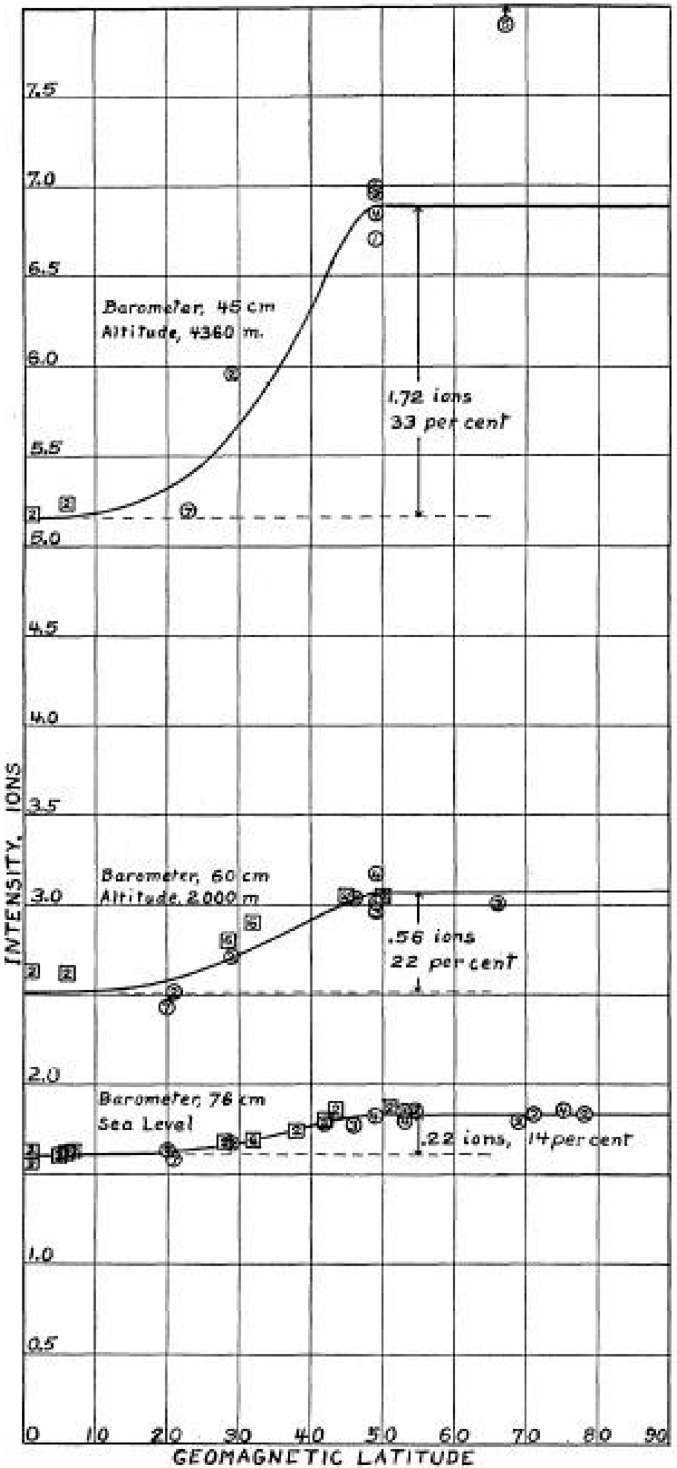
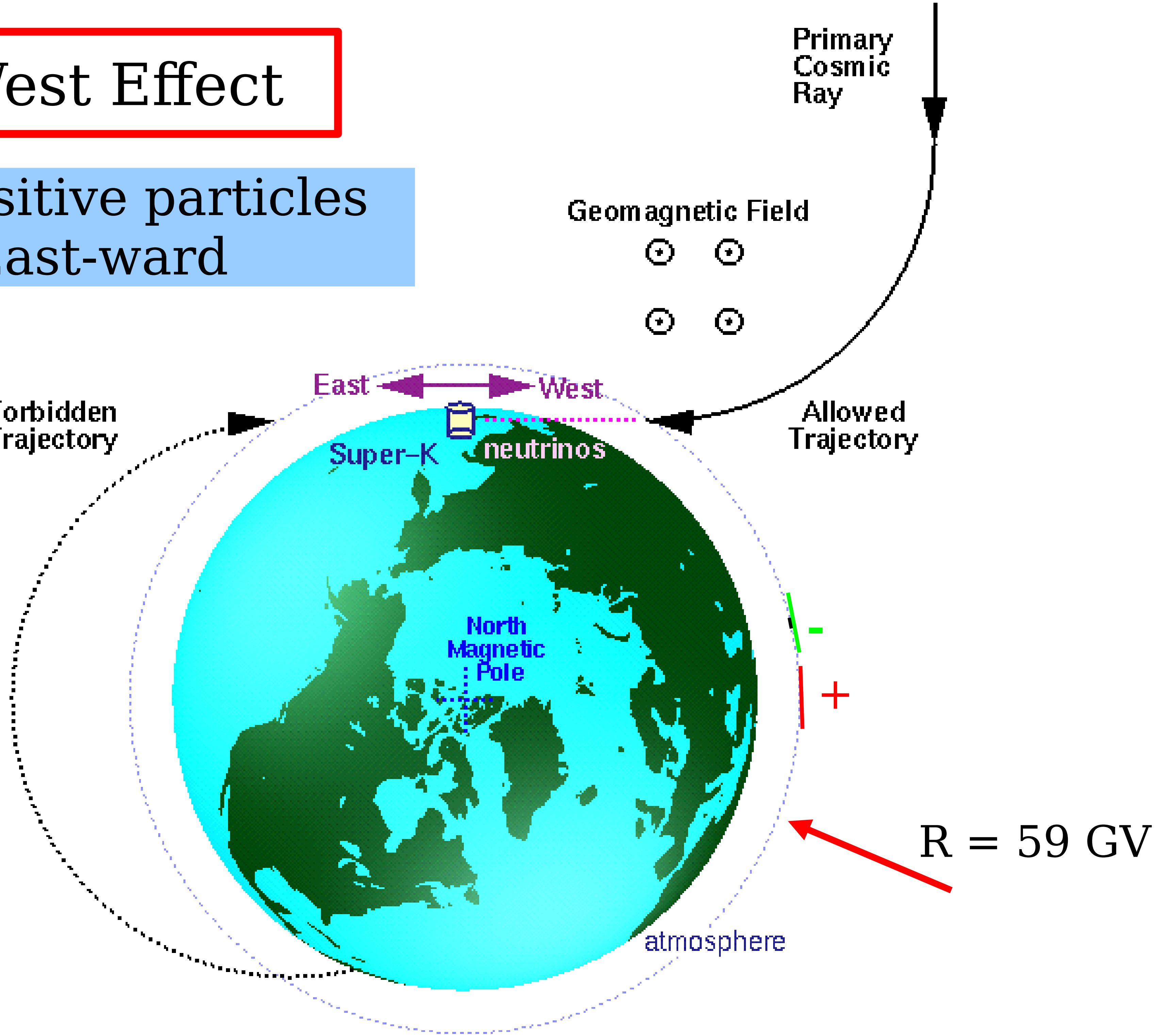


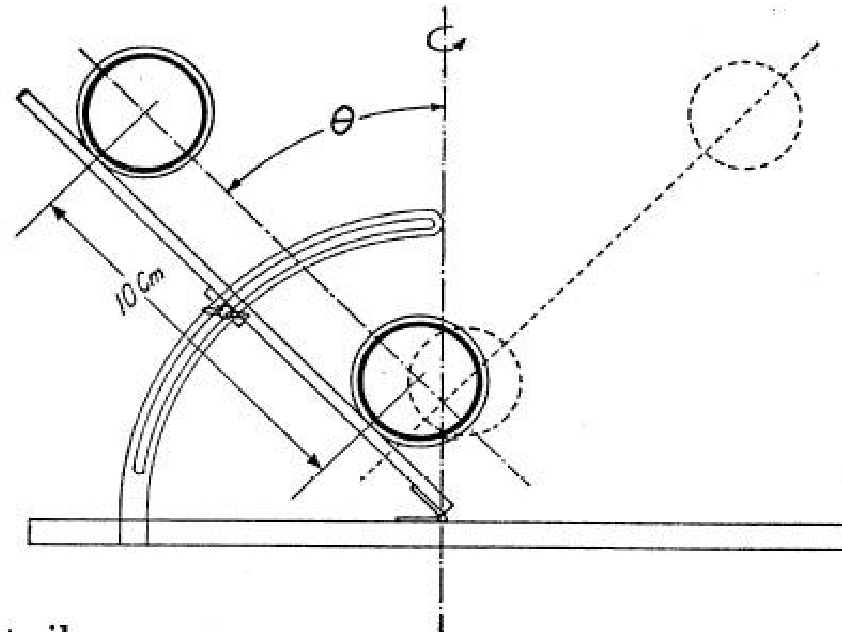
FIG. 6. Intensity *vs.* geomagnetic latitude for different elevations.

East-West Effect

More positive particles going East-ward



Phys. Rev. 43, 835 - 836 (1933)



A Positively Charged Component of Cosmic Rays

Luis Alvarez and Arthur H. Compton
University of Chicago,

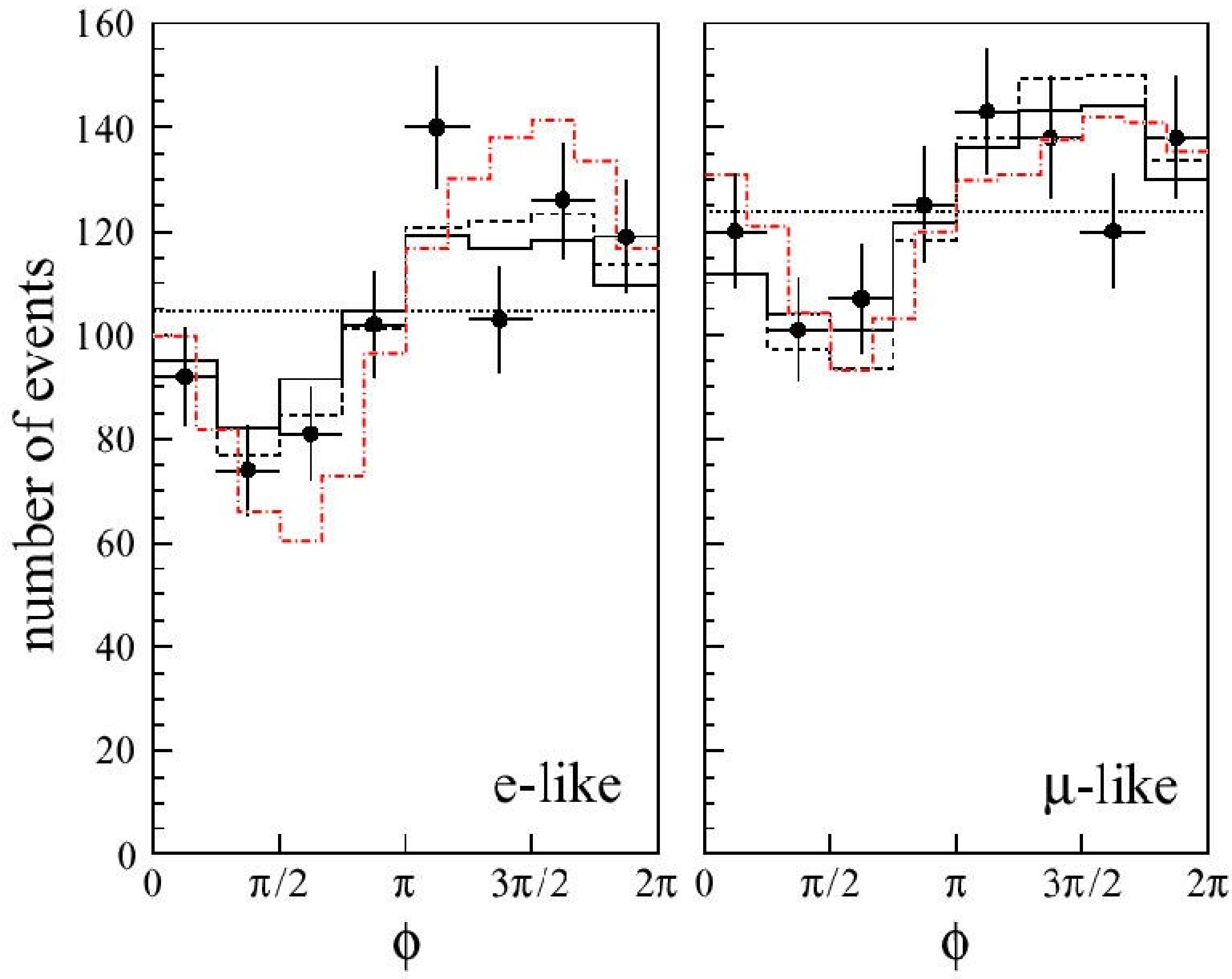
Received 22 April 1933

TABLE I. *East-west measurements at Mexico City, April, 1933.*

Geomagnetic latitude 29°N, elevation 2310 m, barometer, 56.5 cm.

Zenith angle		West	East	West/East
15°	Counts	5370	4856	
	Rate	6.83±0.07	6.64±0.07	1.03±0.02
30°	Counts	4897	4869	
	Rate	5.79±0.06	5.49±0.06	1.055±0.015
45°	Counts	2691	2693	
	Rate	3.70±0.05	3.30±0.05	1.12±0.02

East- West effect with neutrinos measured by Super-Kamiokande



In the absence of a magnetic field the Cosmic Rays would be ISOTROPIC.

(a) Same flux in different points of the Earth

(b) Same flux for different directions

The Earth has a magnetic Field
(in first approximation a Dipole Field)

At the surface:
B_{poles} = 0.6 Gauss (6×10^{-5} T)
$B_{equator}$ = 0.3 Gauss (3×10^{-5} T)

The geomagnetic field forbids
low RIGIDITY particles to reach the surface
of the Earth from outside the solar system.

RIGIDITY = Momentum / Electric Charge
[GV / c] [GeV / c] / e

For an exactly **dipolar field**
Analytic solution (Stormer):

Rigidity = p/Ze

All allowed trajectories have $R > R_{cutoff}(r, \lambda, \Omega)$

Stormer Cutoff

$$R_S(r,\lambda,\theta,\varphi) = \boxed{\left(\frac{M}{2r^2}\right)} \left\{\frac{\cos^4\lambda}{[1+(1-\cos^3\lambda\sin\theta\sin\varphi)^{1/2}]^2}\right\}$$

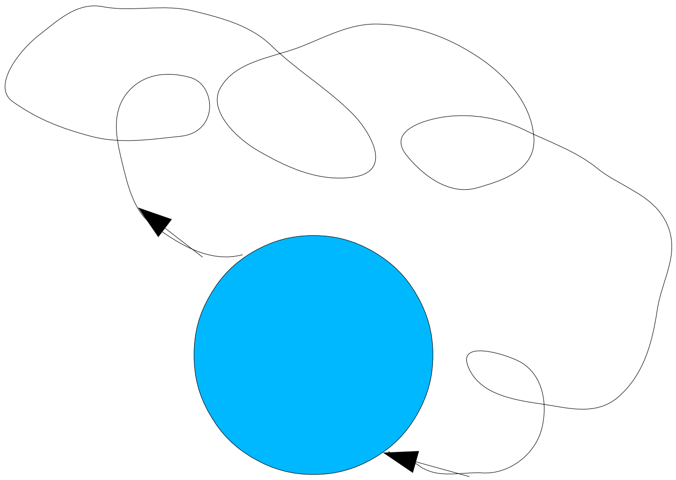
59 GV

M = magnetic moment of the dipole

r = distance from center
λ = Magnetic Latitude
θ, ϕ = local zenith and azimuth angles

An Observer at point A
does not observe a Cosmic Ray arriving from
the Direction Ω with Rigidity $R = p/Ze$
because it shoud originate from the surface of the Earth.

"Forbidden Trajectory"



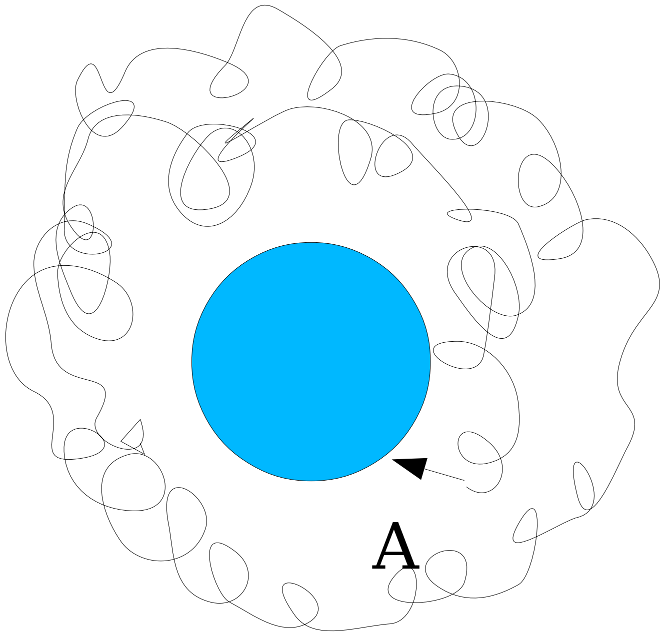
A trajectory is identified by:

Position on the Earth
Direction
Rigidity

For forbidden trajectories
the flux must be zero

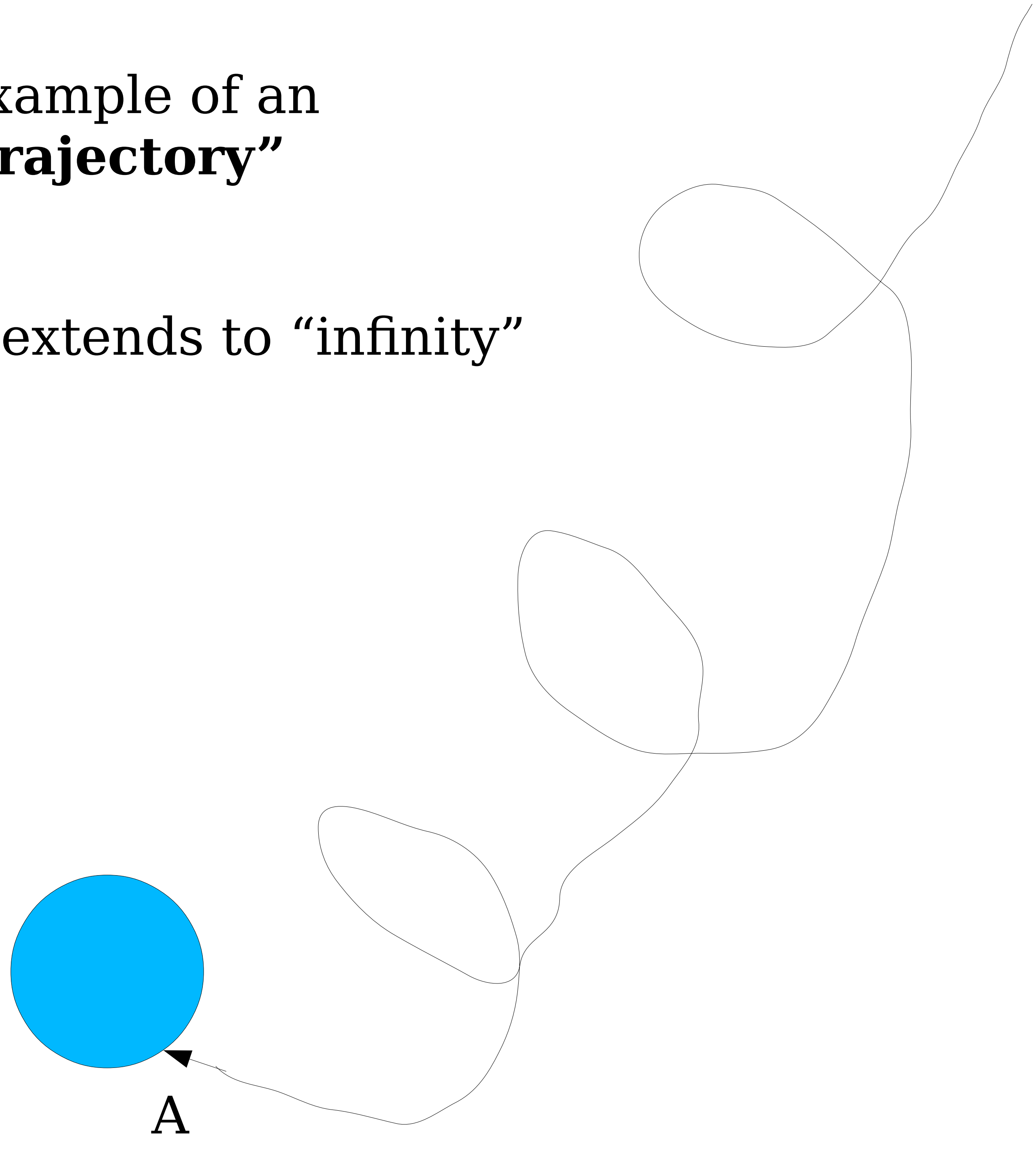
A different case of a
“Forbidden Trajectory”

Remains confined in the vicinity of the Earth



This is an example of an
“Allowed Trajectory”

Because it extends to “infinity”



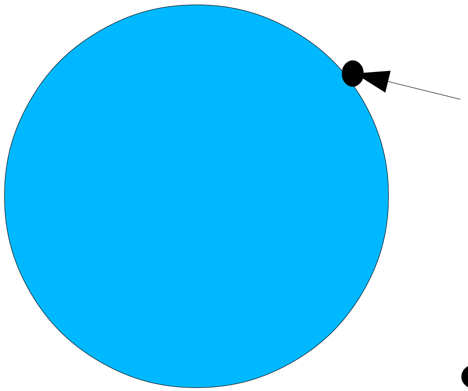
The magnetic field prevents low rigidity particles from reaching the surface of the Earth.

IF:
The intestellar flux is isotropic
the e.m. Field around the Earth is purely magnetic
from the LIOUVILLE theorem one obtains:

$$\phi_{\vec{x}}(p, \Omega) = \phi_{\infty}(p) \times \zeta(p, \Omega, \vec{x})$$

ζ is either 0 or 1

- Flux is ISOTROPIC at large distances from the Earth $\Phi(p)$
- Space is filled with a static Magnetic Field



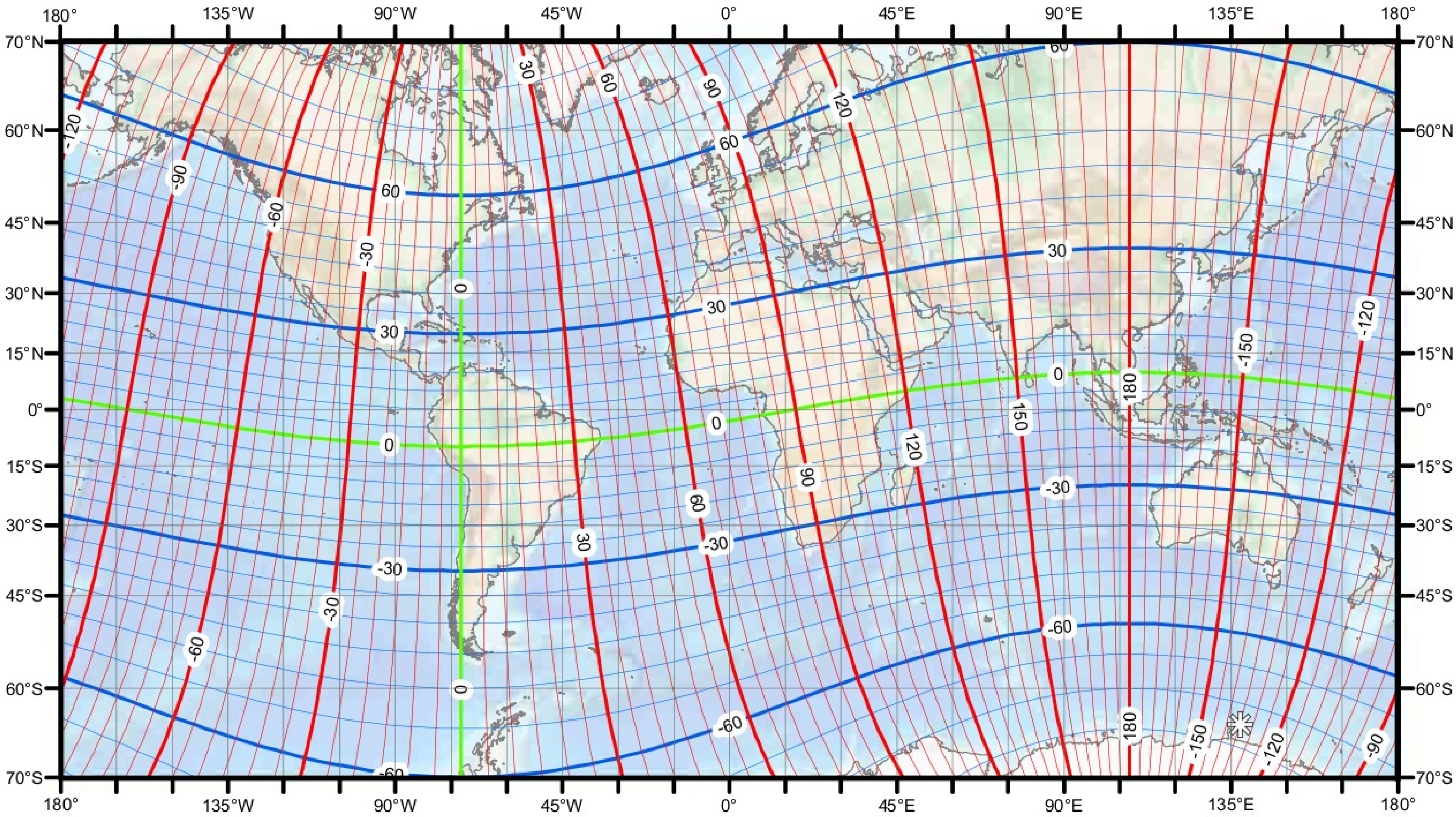
Point A

Flux at point A:

$$\Phi\,(p,A,\Omega) = \Phi\,(p) \text{ or } 0$$

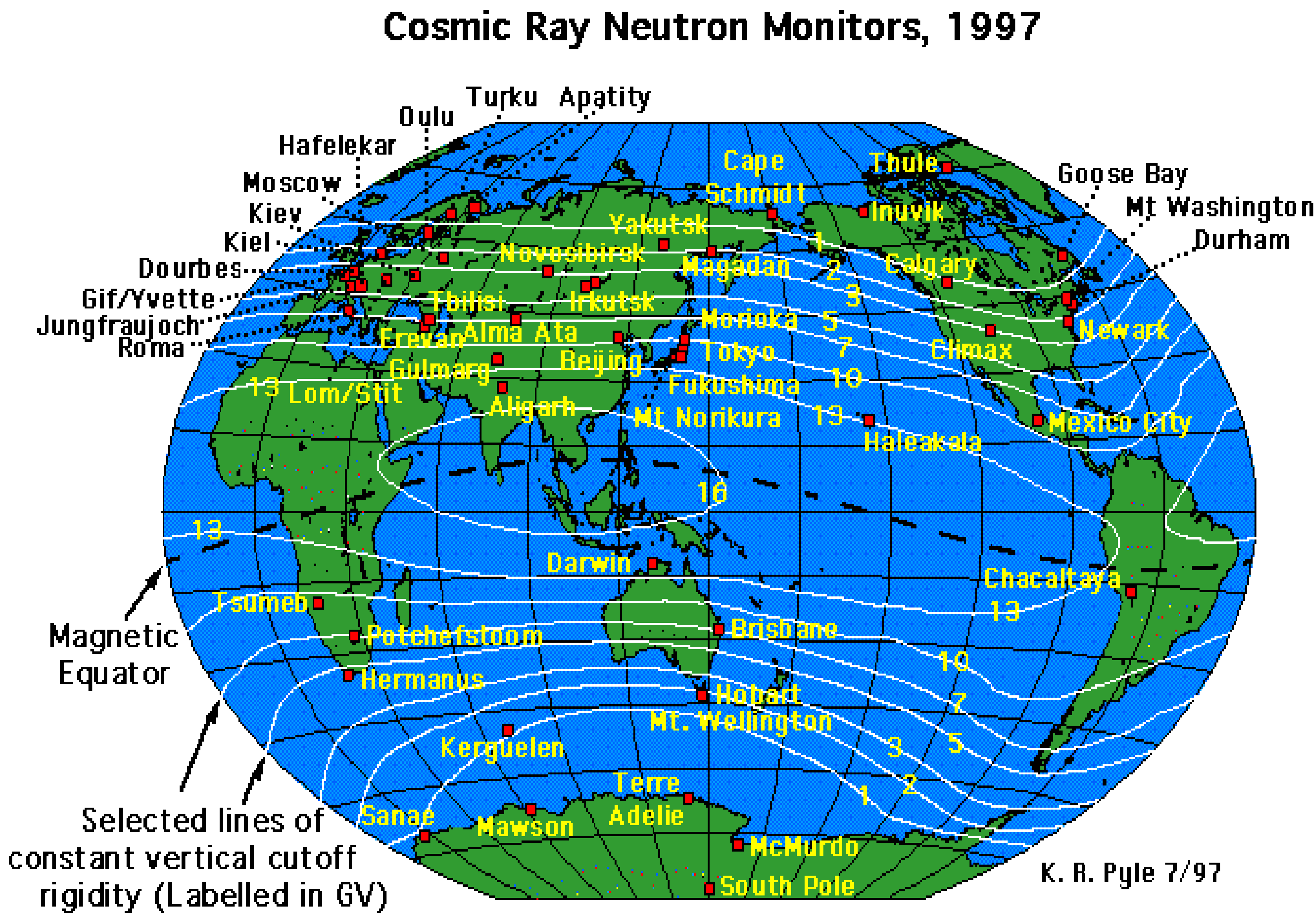
Allowed Trajectory	$\Phi\,(p)$
(Forbidden)	0

US/UK World Magnetic Chart -- Epoch 2010
Geomagnetic Coordinates



Units: degrees
Countour Interval: 5 degrees
Map Projection: Mercator

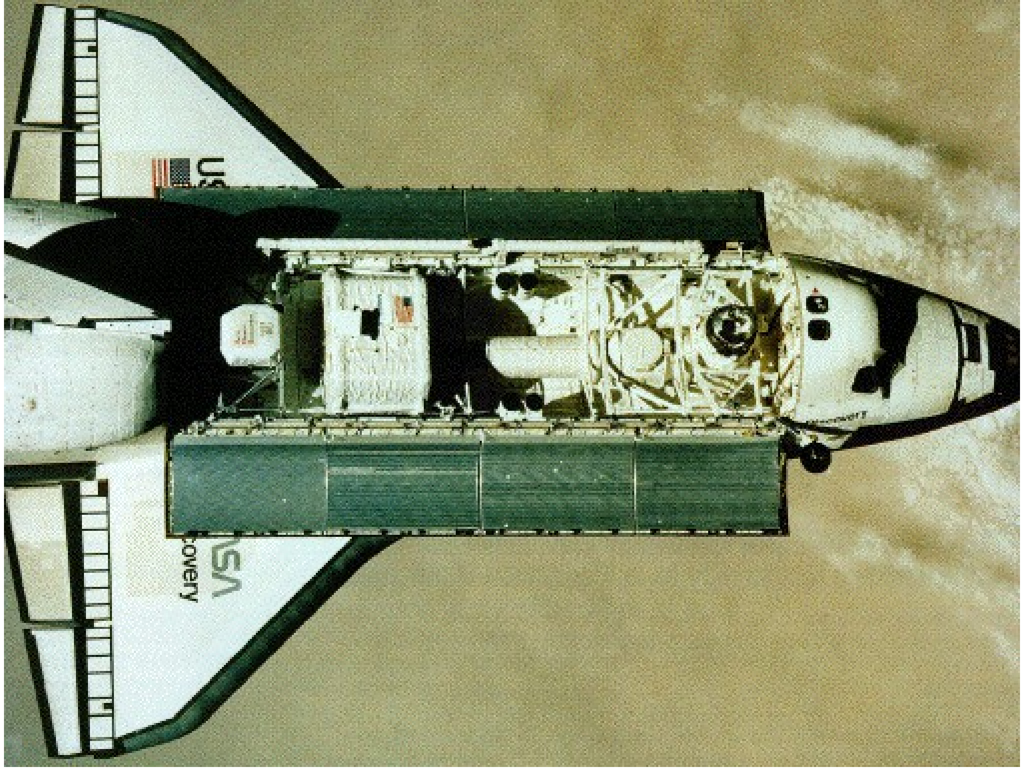
LINES OF vertical rigidity cutoff cutoff

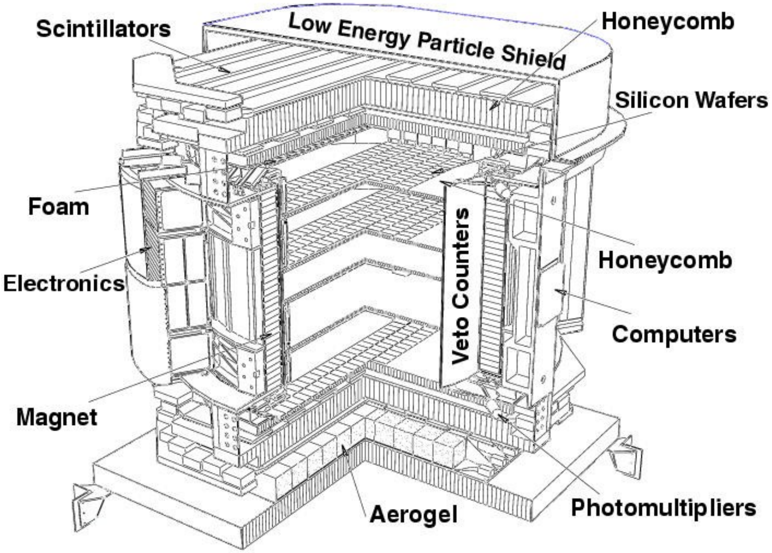


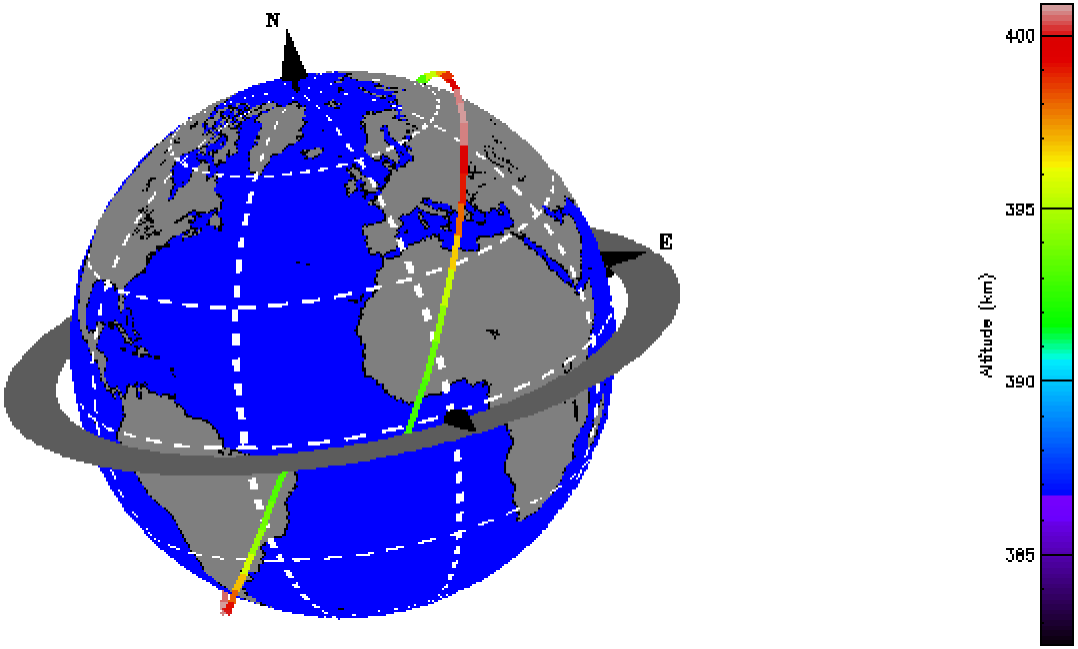
AMS-01 detector

10 days flight
june 1998

AMS orbit
h = 400 Km
inclination 57^{0}

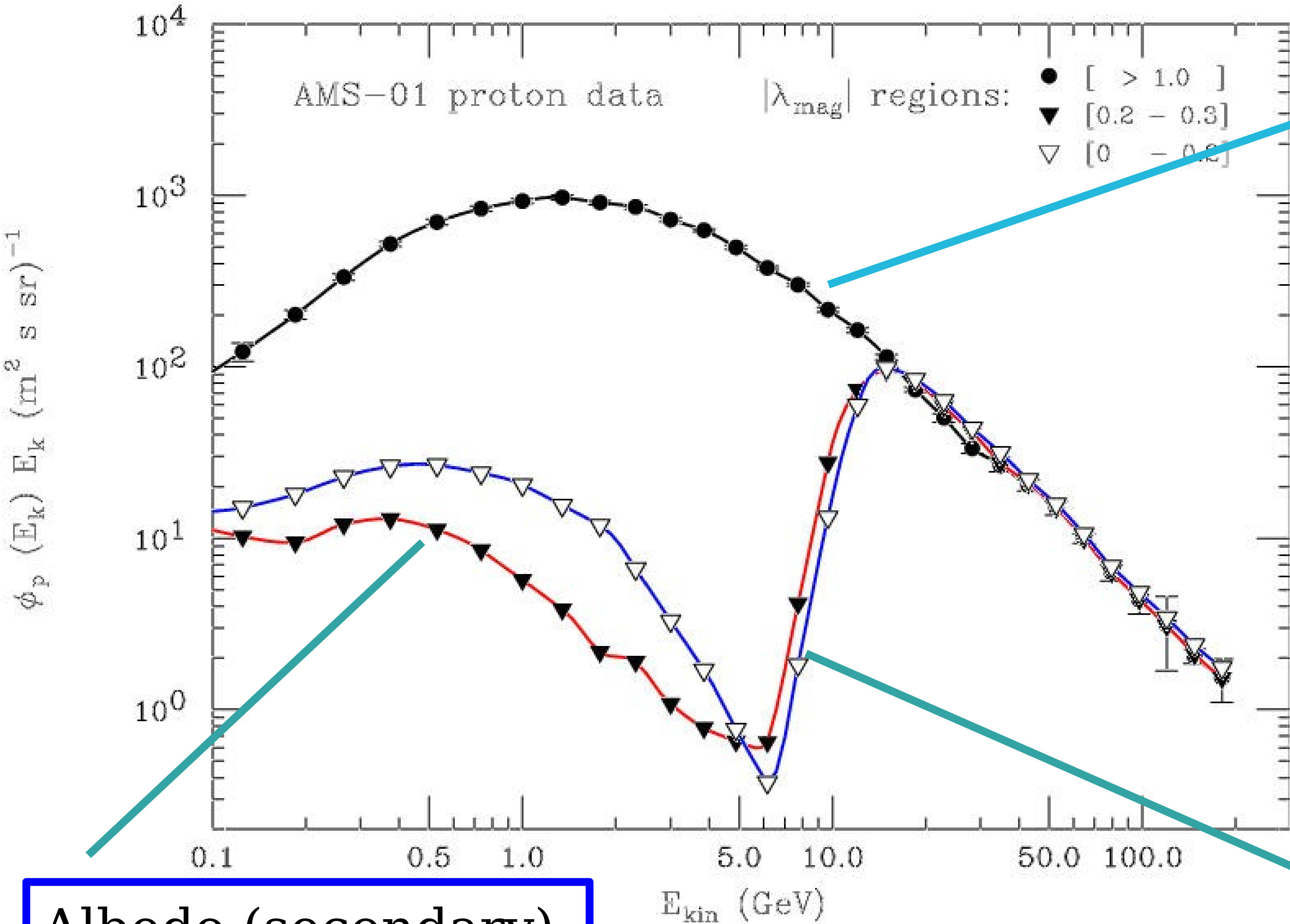






Proton Measurements

$\lambda_{mag} < 0.2$ (11.5^0)



Primary Flux

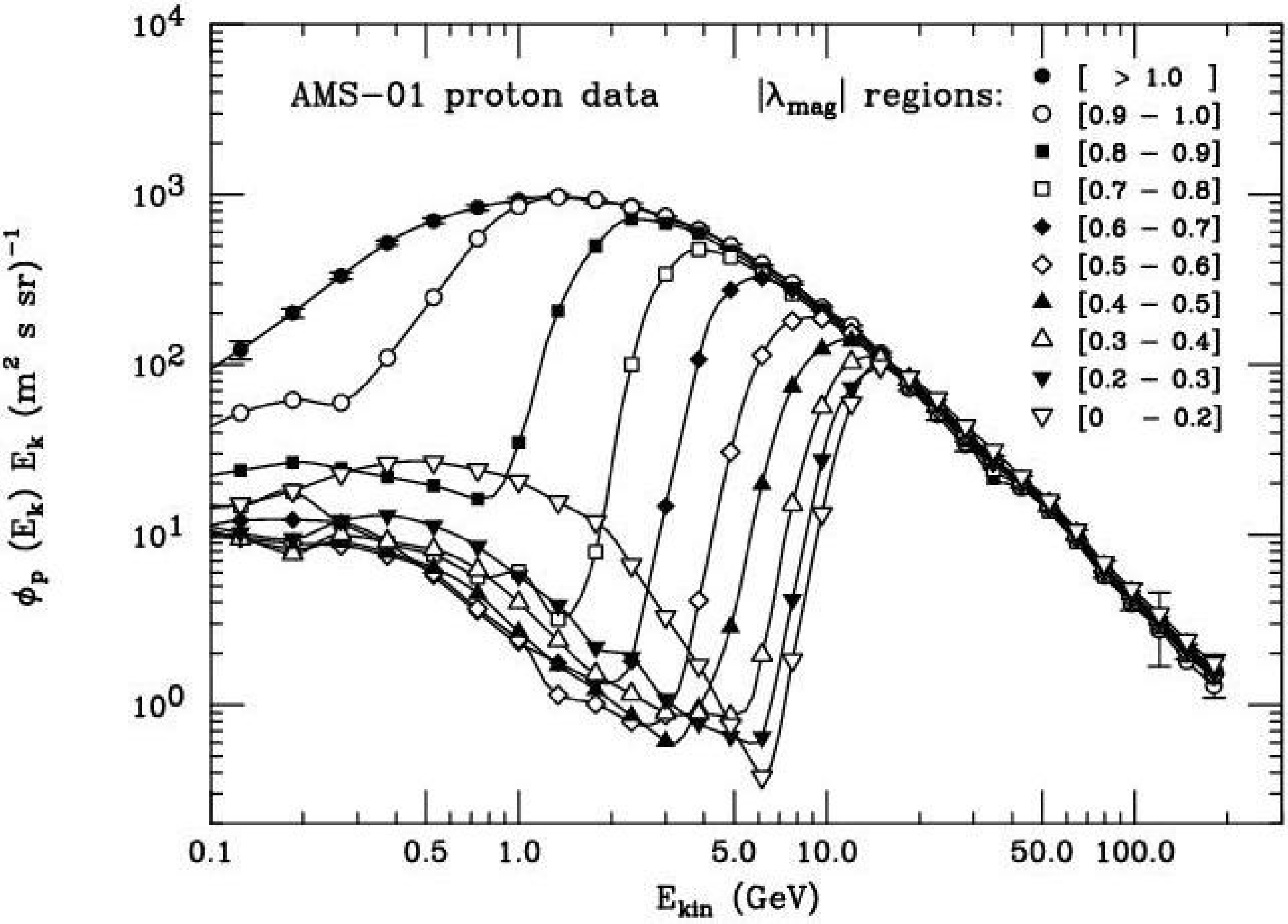
Albedo (secondary) Flux

Geomagneti
Cutoff

Geomagnetic Effects

AMS-01 Measurements over different regions of the

Orbit inclination 51.7 degrees



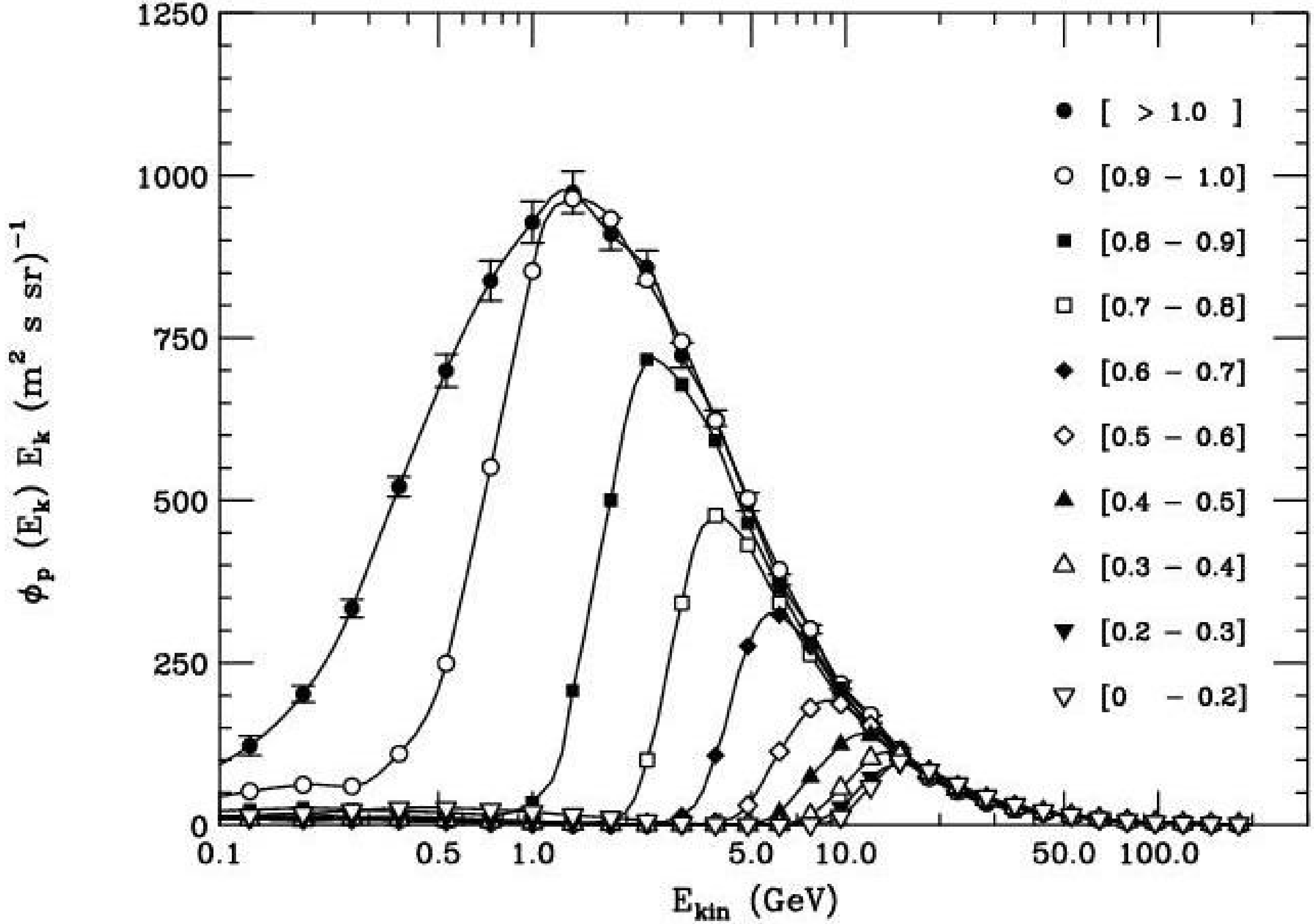
Measurements in different regions of Magnetic Latitude

CUTOFF

sub-cutoff particles

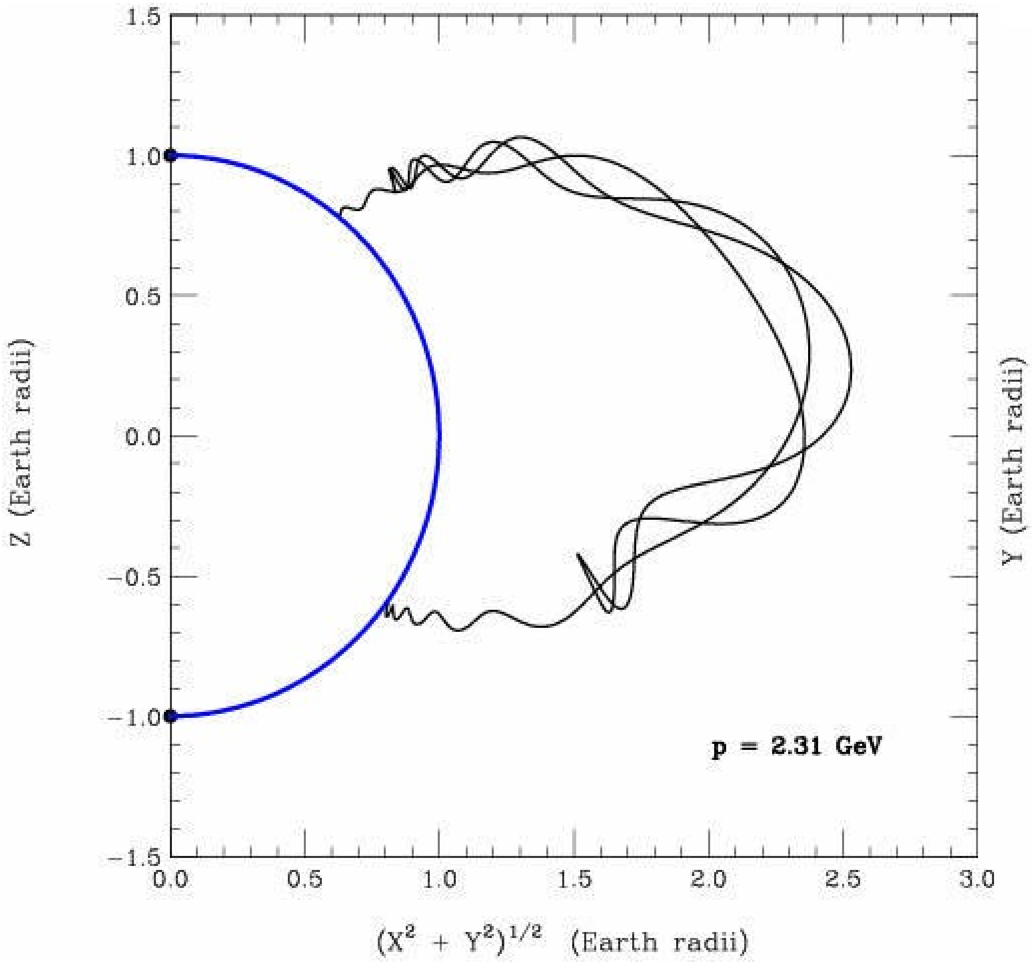
Geomagnetic Effe

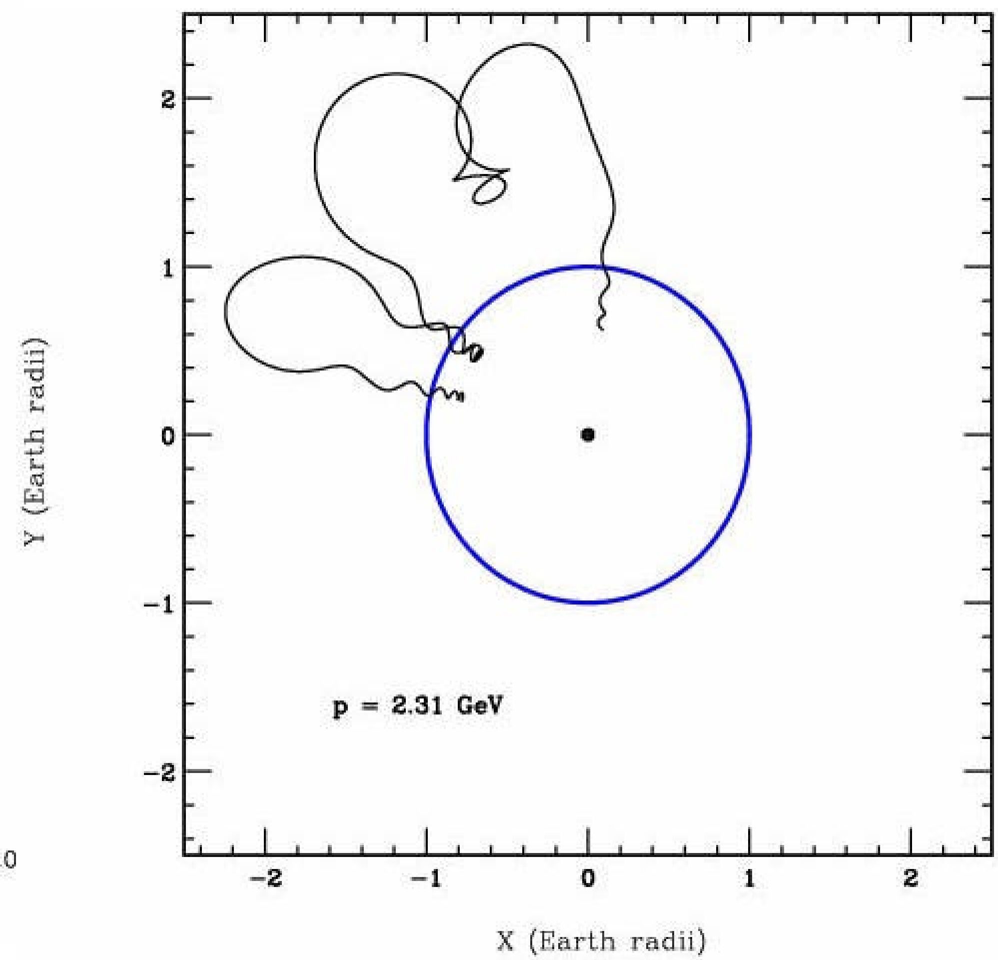
AMS-01 Measurements over different regions of the



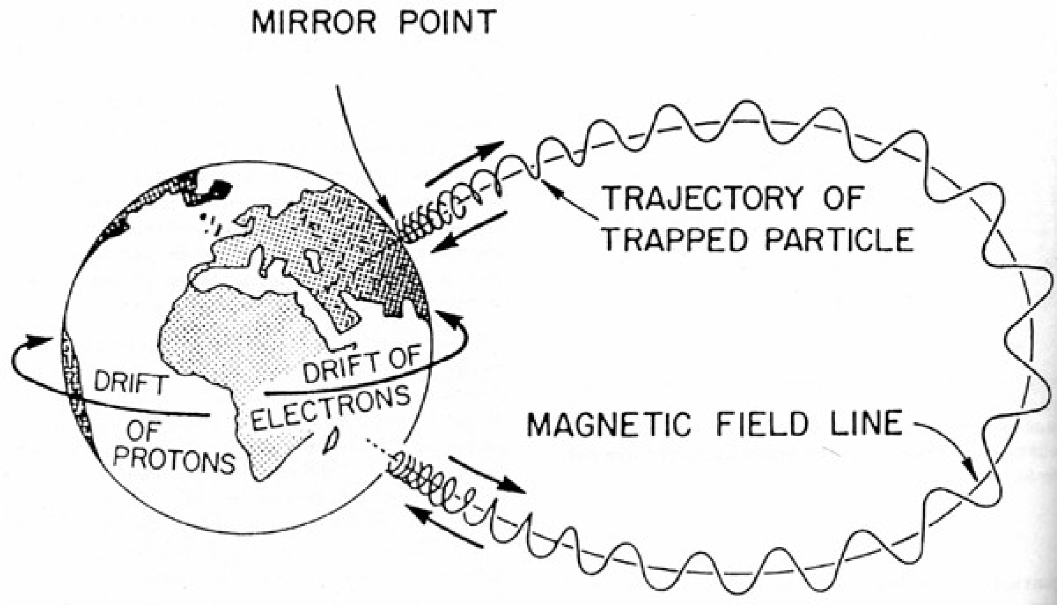
Magnetic Latitude

Albedo Particles

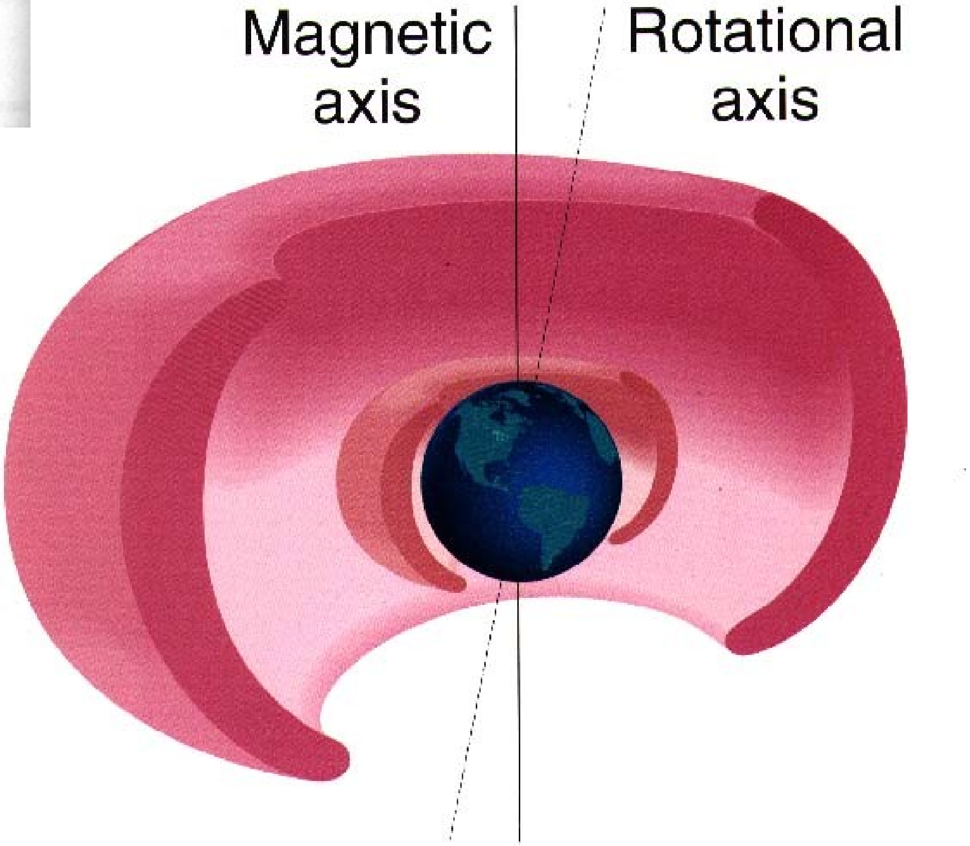




Trajectory of trapped particle



Van Allen Belts

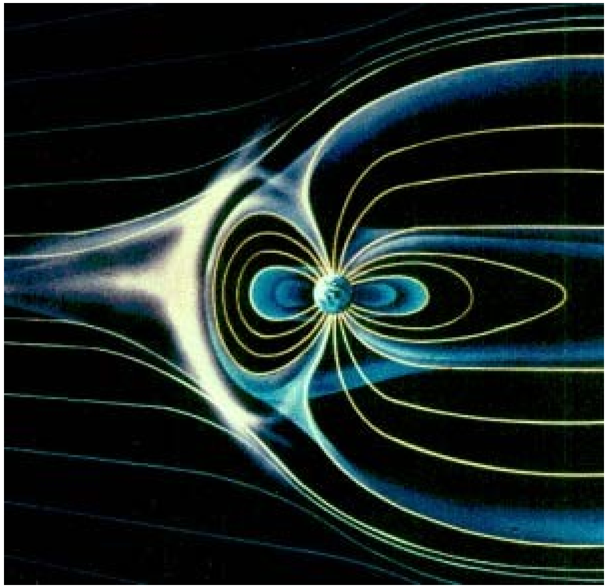


Time variations of Primary Cosmic Rays

The density of Cosmic Rays in interstellar space is essentially constant in time.

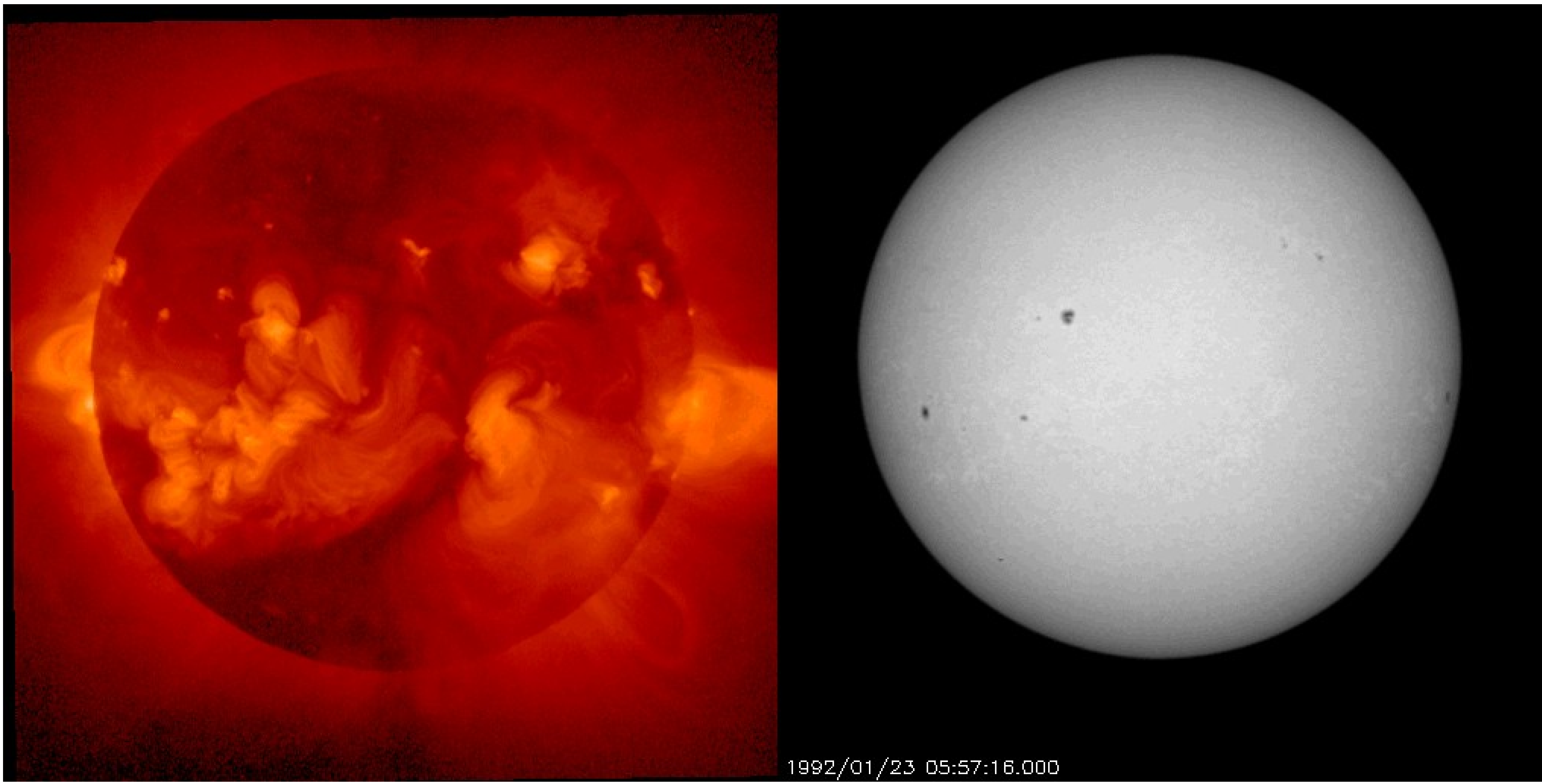
The density at 1 Astronomical Unity from the sun (the Earth orbit radius) has a small time dependence due to the effects of the solar wind.
The solar magnetic activity varies with a **(11 + 11) years periodicity**.

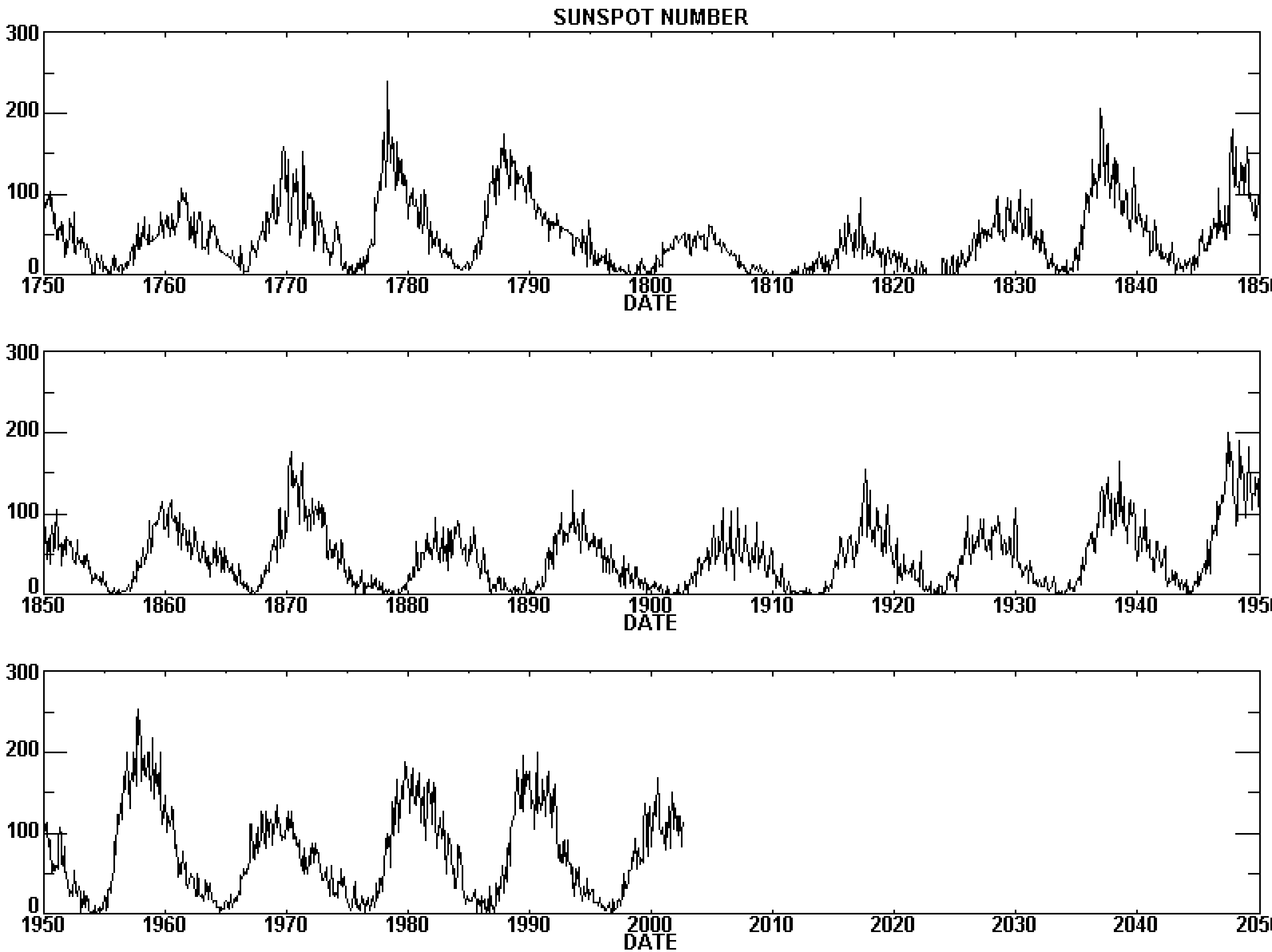
SOLAR WIND, stream of plasma
continuously emitted from the sun
that travel with a velocity of approximately 450 Km/s



SUNSPOTS: signals of solar activity.

X-rays **Visible light**

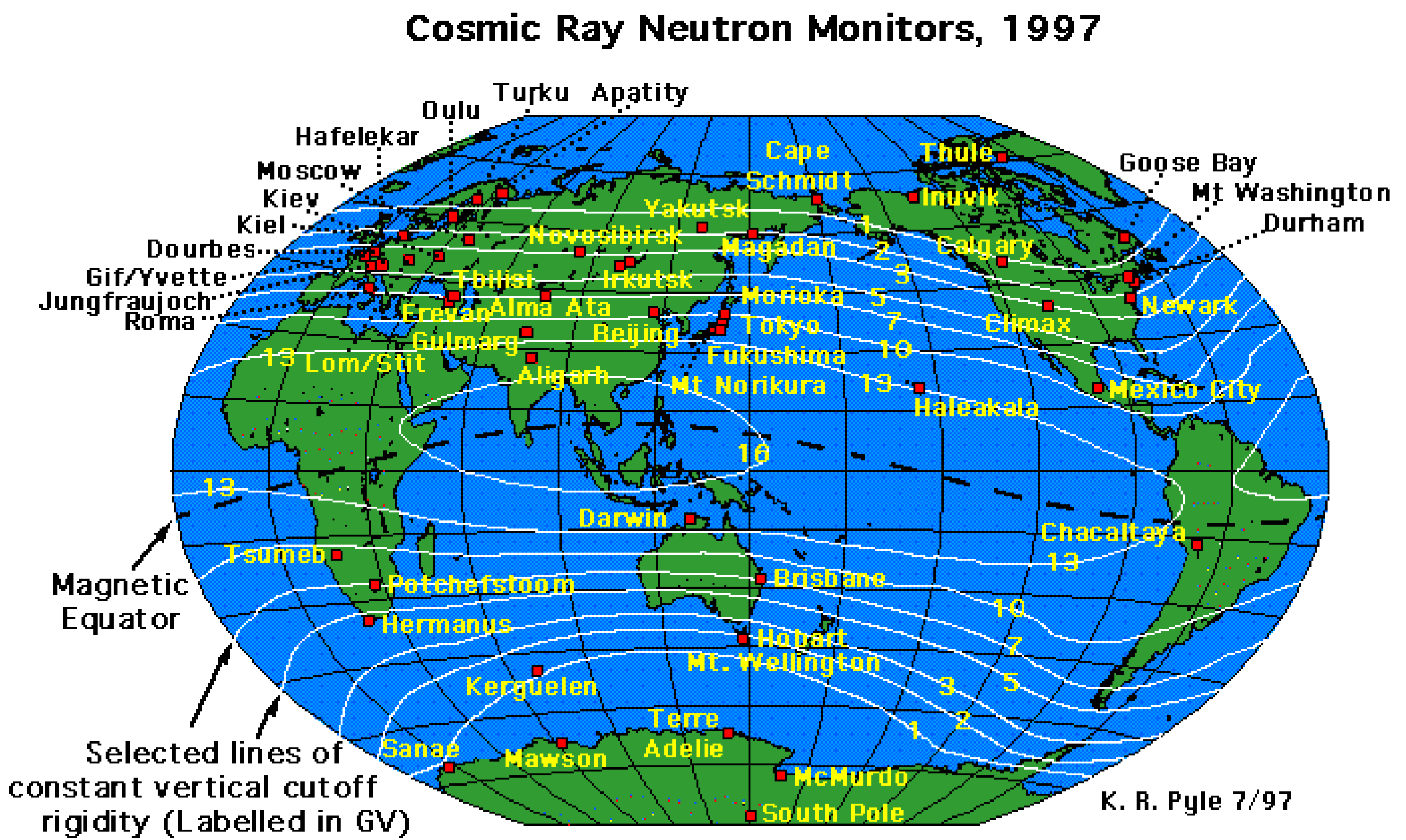




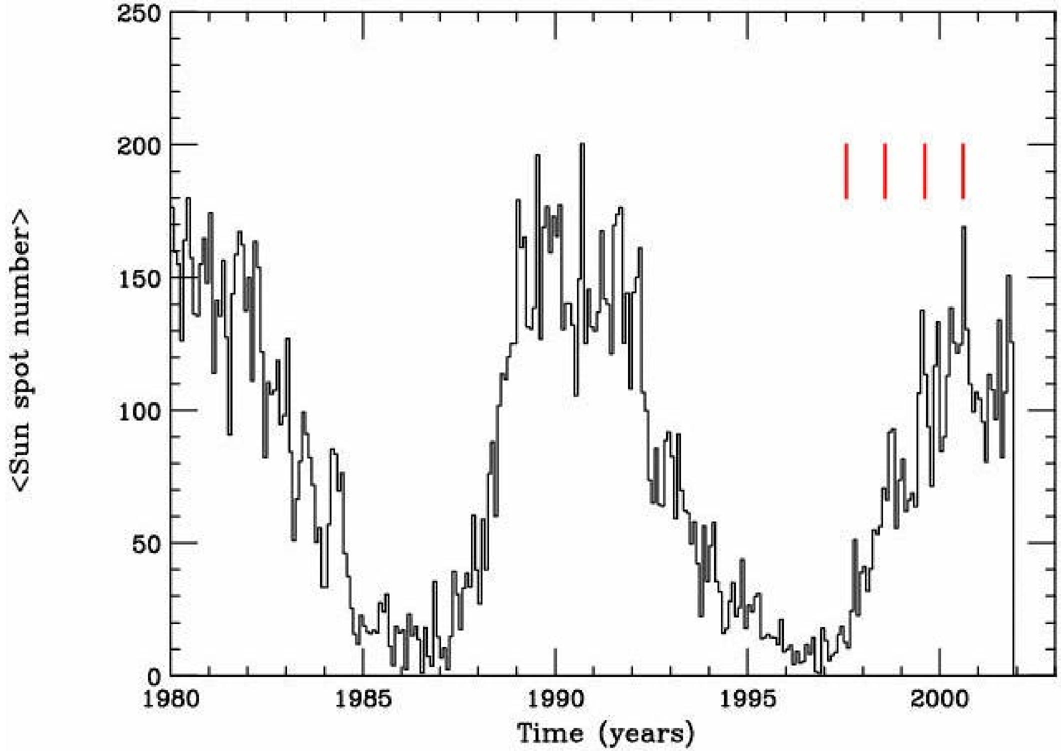
SUNSPOT NUMBER
300
200
100
0
1750
1760
1770
1780
1790
1800
1810
1820
1830
1840
DATE
300
200
100
0
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
DATE
300
200
100
0
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
DATE

Neutron Monitors

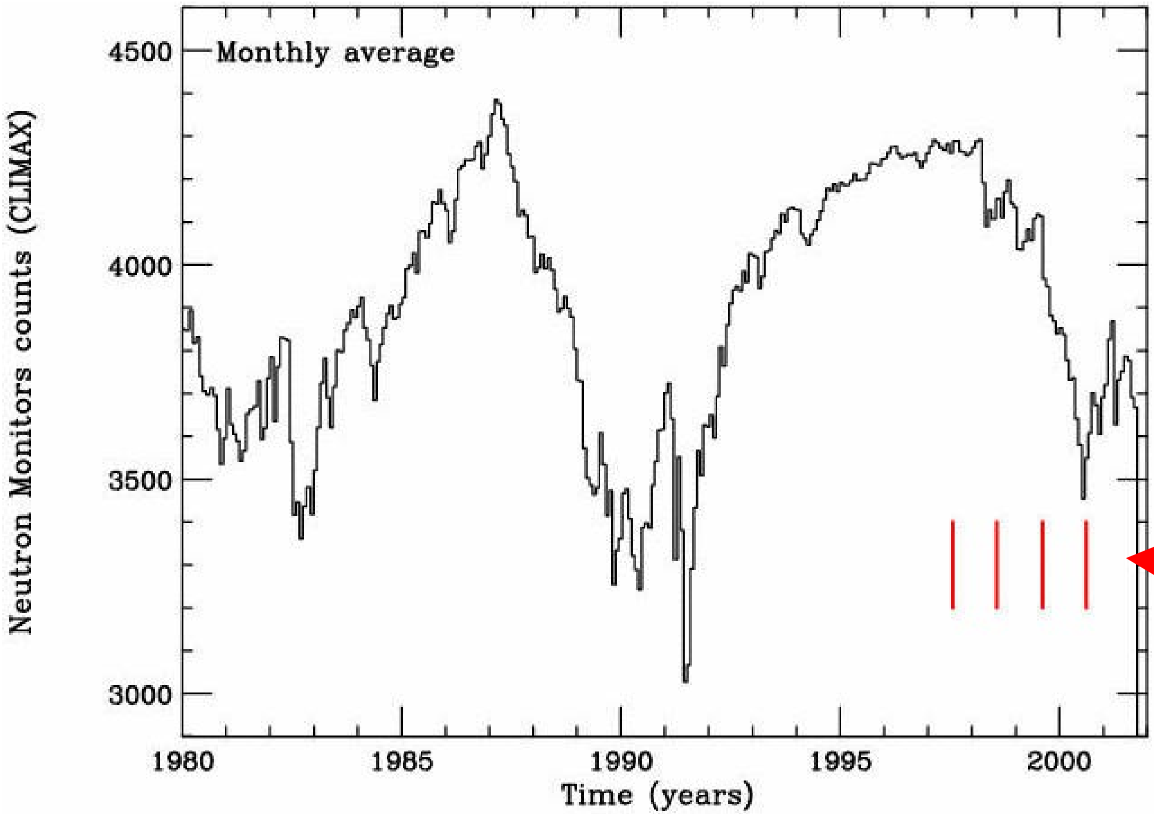
Measure the flux of **neutrons** produced by the evaporation of Air nuclei by primary cosmic rays



Sunspot number

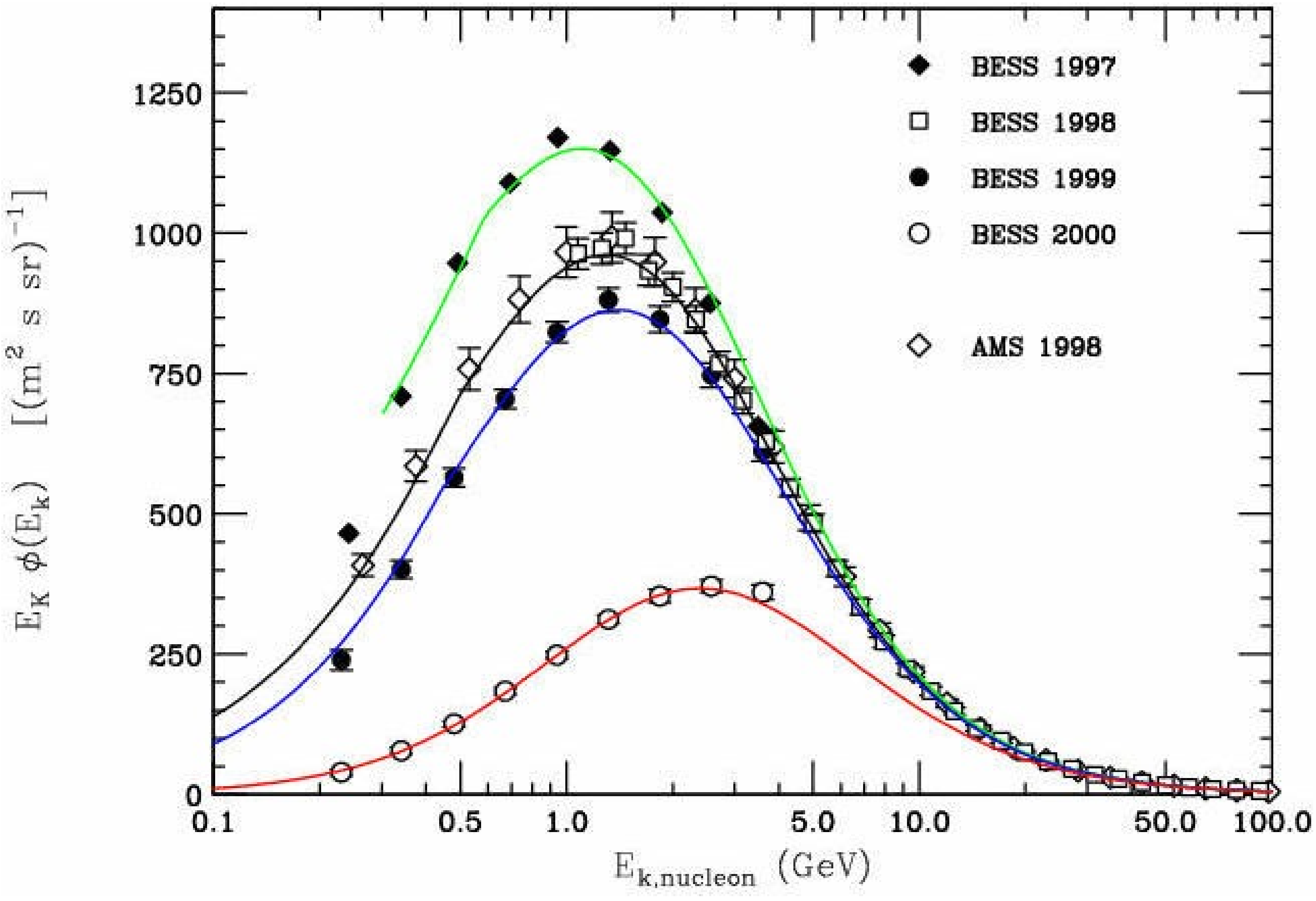


Neutron Monitor Counts



Time of BESS flights:

BESS proton flux MEASUREMENTS



Interstellar Cosmic Ray Flux

very close to the observed flux for E > 20-30 GeV

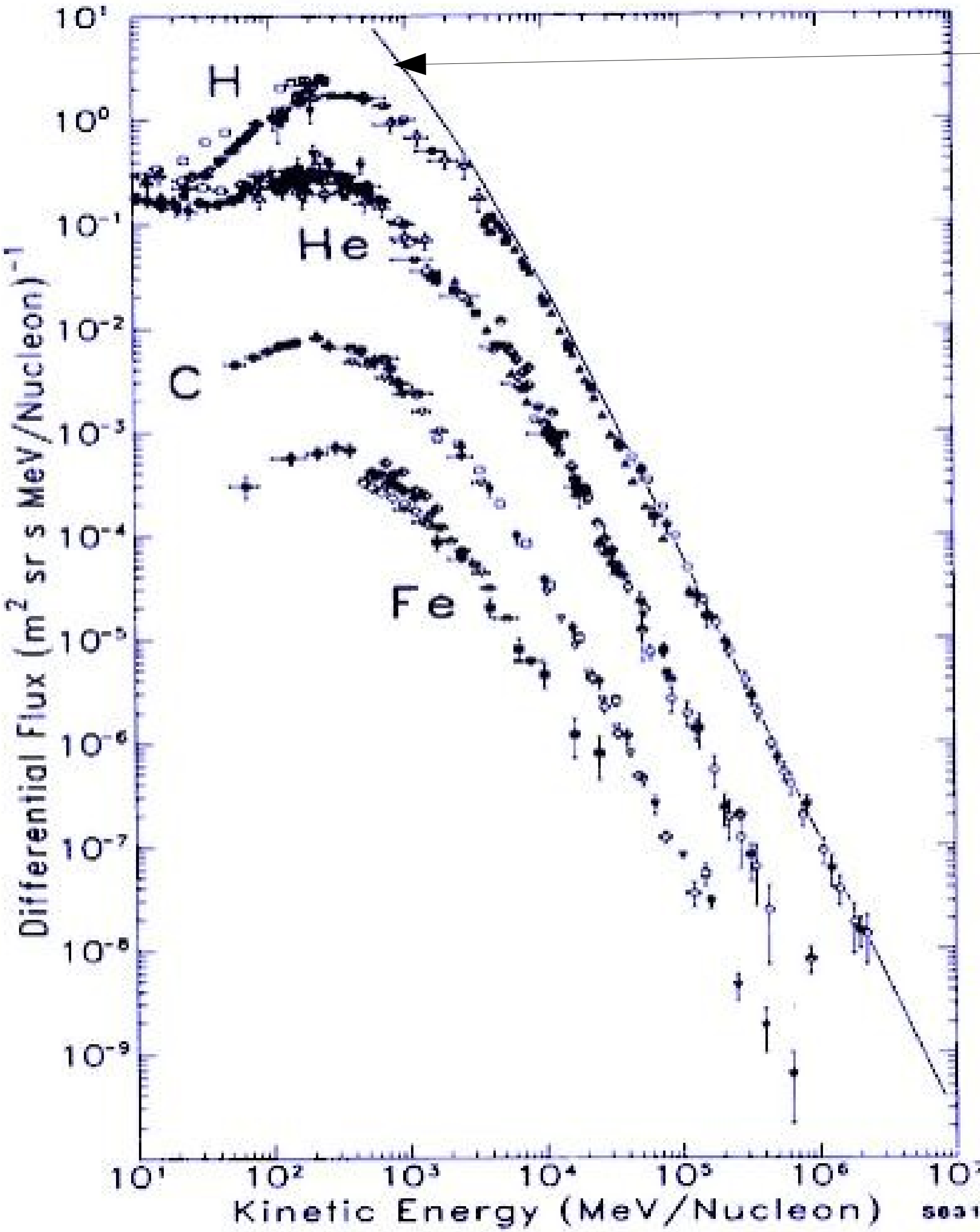


Figure 2. The differential energy spectra of the primary cosmic ray H, He, C, and Fe at Earth. [*Reproduced with permission from J. A. Simpson (1983).* Ann. Rev. Nucl. Part. Sci. **33** *by Annual Reviews, Inc.*].

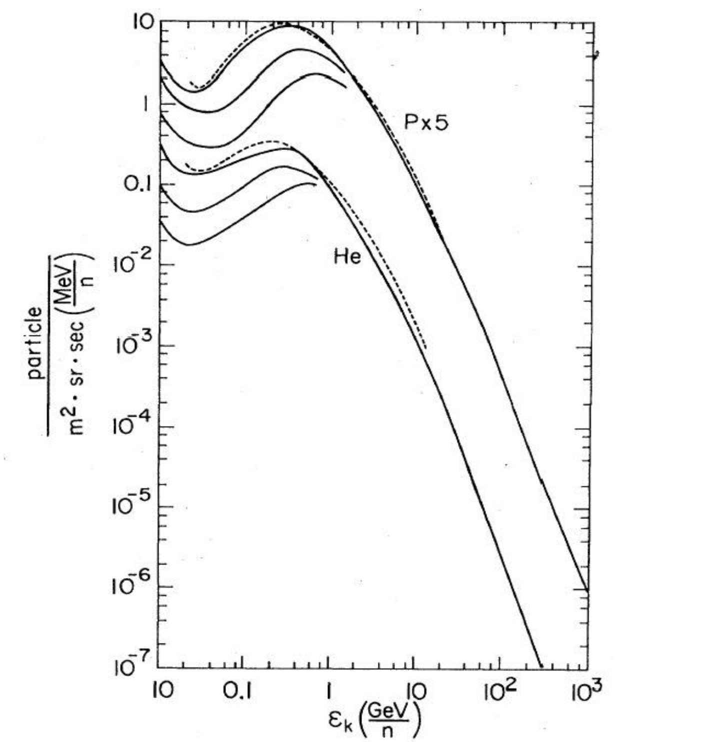
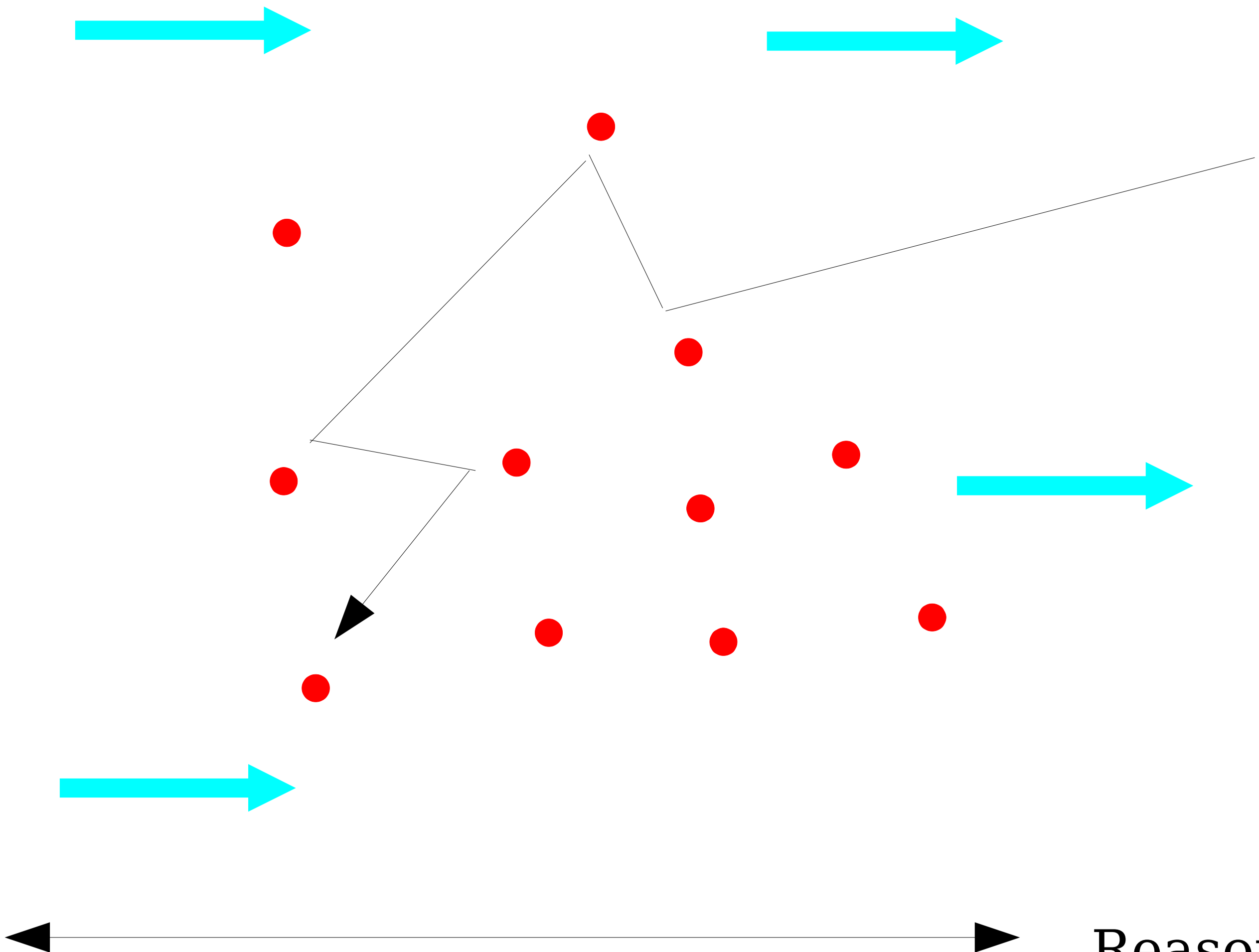


FIG. 1. Spectra of hydrogen (intensity p is multiplied by 5) and helium. Several curves at low energies correspond to the measurements in different periods of Solar activity.

Moving magnetic scattering centers



Reasonably good approximation:

The effect of the solar wind
is equivalent to a POTENTIAL
with particles losing an energy
$\Delta E = Z V$

$$\mathbf{E_f = E_i - Z\,\Delta V}$$

Time Variations of Cosmic Rays

Induced by variations in intensity of the solar wind

Reasonable approximation for the description of the modulation is the FORCE FIELD approximation.
The effect of the wind is equivalent to a potential

A single parameter controls the variation of the spectra

$$E_{earth} = E_{inter\ stellar} - Z\ V_{solar\ wind}(t)$$

V ~ 1 GeV

$$\Phi_{earth}(E,t) = (p_{earth}/p_{i.s.})^2 \quad \Phi_{inter\ stellar}[E + V(t)]$$

The COSMIC RAY FLUX is
to a very good approximation

ISOTROPIC

Charged Particles lose memory of
their initial direction
because of the bending in the
galactic Magnetic Field

Magnetic Confinement of Cosmic Rays in the Galaxy.

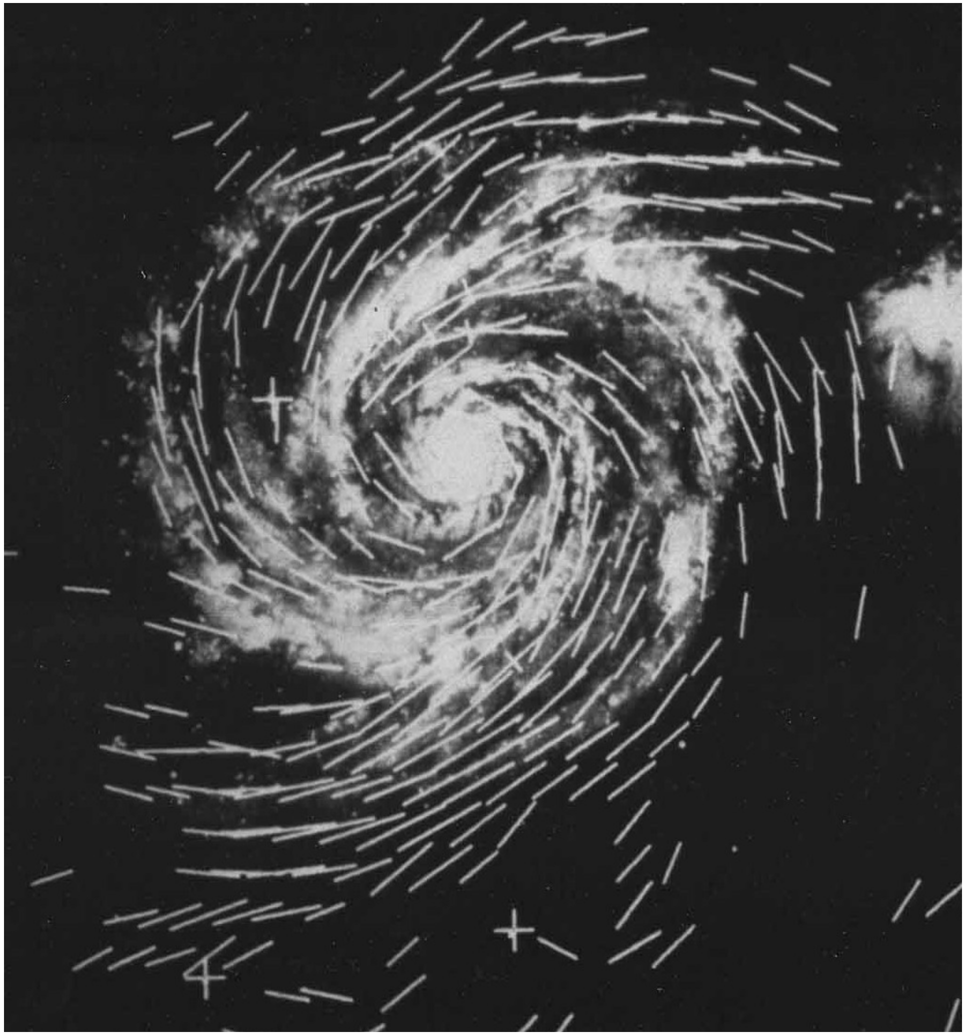
The Galaxy is filled with a magnetic field with an average value of 3-10 μG.

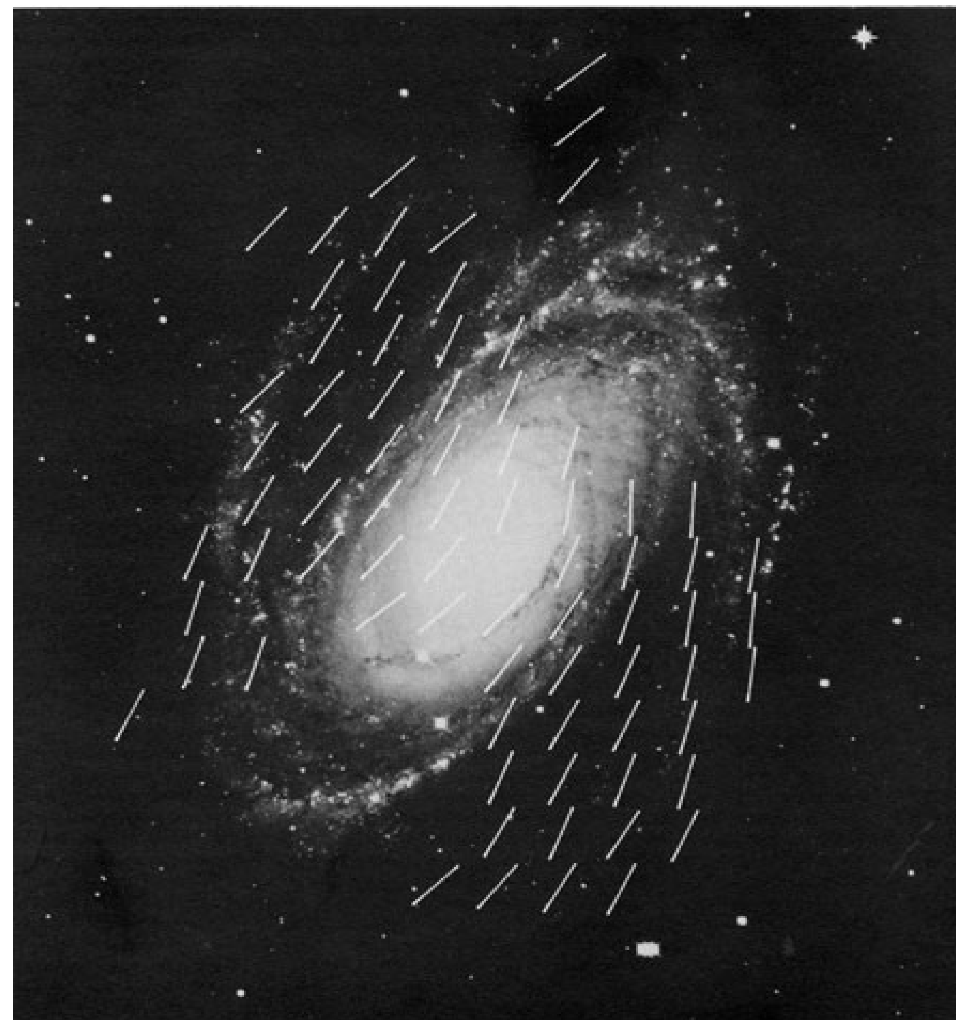
Charged particles remain confined by this magnetic field.

$$r_{\mathrm{Larmor}} = \frac{E\ \beta_\perp}{ZeB}$$

$$r = \frac{1}{300}\ \frac{E(\mathrm{eV})\ \beta_\perp}{Z\ B(\mathrm{Gauss})}\ \mathrm{cm}$$

GALACTIC MAGNETIC FIELDS





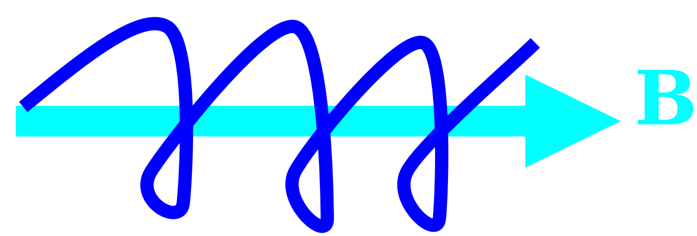
"Regular Field"

"Random Field"
(turbulent motions)

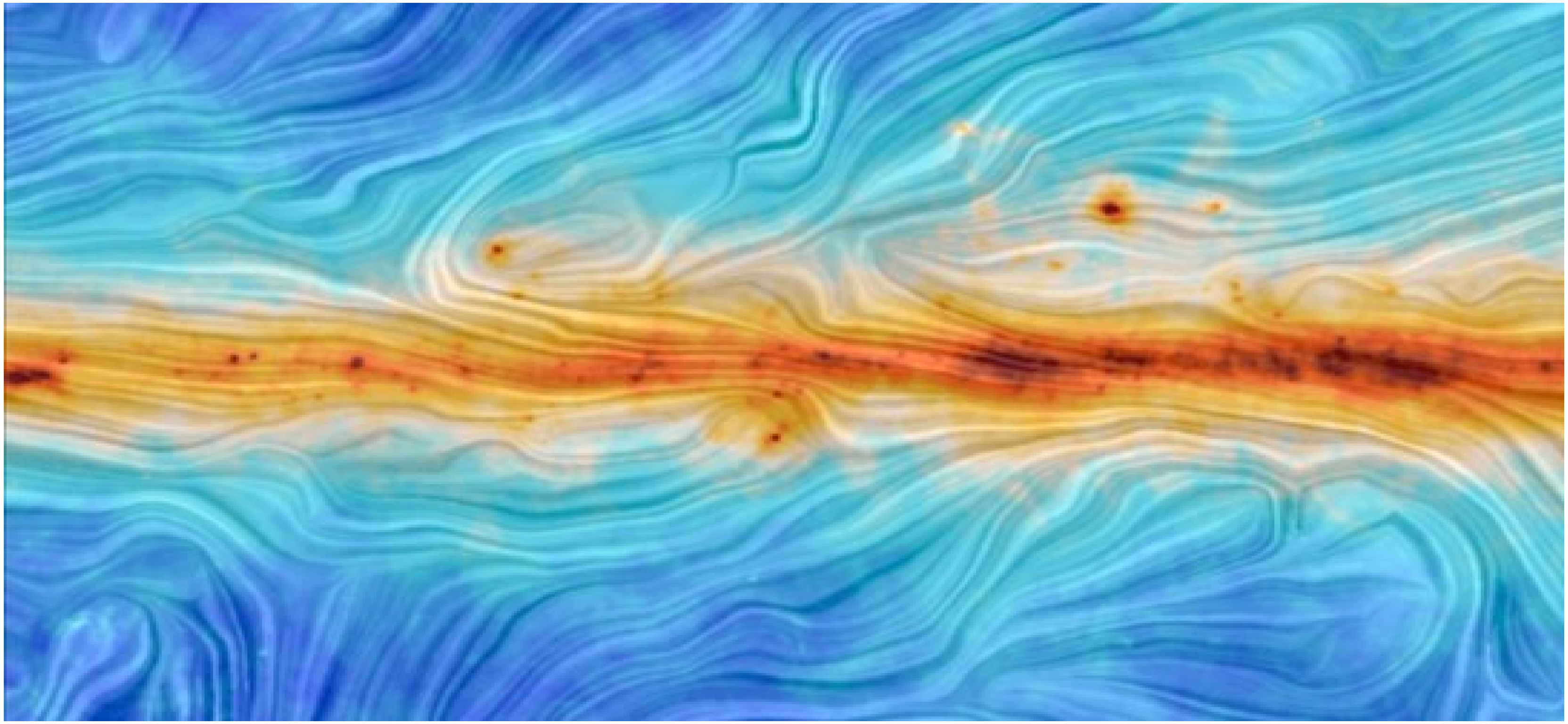
Most Cosmic Rays are
produced inside the Galaxy,
by “Cosmic” accelerators

They remain confined
in the galaxy for a time
of order **10 Million years.**

The Magnetic Field
“scramble” the trajectories
of Cosmic Rays
make them isotropic.



Measurement of magnetic field in the Galaxy by Planck.



Measure of the polarized light emitted by dust grain
Color: dust density
Texture: direction and intensity of magnetic field

$$\langle B_{\mathrm{galaxy}} \rangle \simeq 3\ \mu\mathrm{Gauss}$$

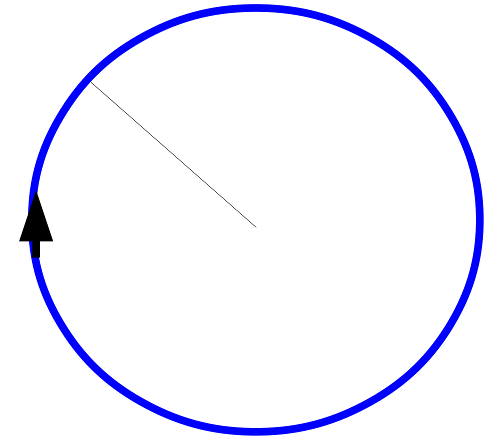
$$\vec{B} = \vec{B}_{\mathrm{regular}} + \vec{B}_{\mathrm{random}}$$

"Regular Field"
(along the spiral Arms)
+
"Random" (Turbulent)
Field

$$\rho_B = \frac{B^2}{8\pi} \simeq 0.22\ \frac{\mathrm{eV}}{\mathrm{cm}^3}$$

Energy
Density

$$r_{\mathrm{Larmor}} = \frac{E\ \beta_{\perp}}{ZeB}$$



$$r = \frac{1}{300}\ \frac{E(\mathrm{eV})\ \beta_{\perp}}{Z\ B(\mathrm{Gauss})}\ \mathrm{cm}$$

$$r = 1.08\frac{E(10^{15}\ \mathrm{eV})}{Z\ B(\mathrm{microGauss})}\ \mathrm{parsec}$$

Parallax Measurements

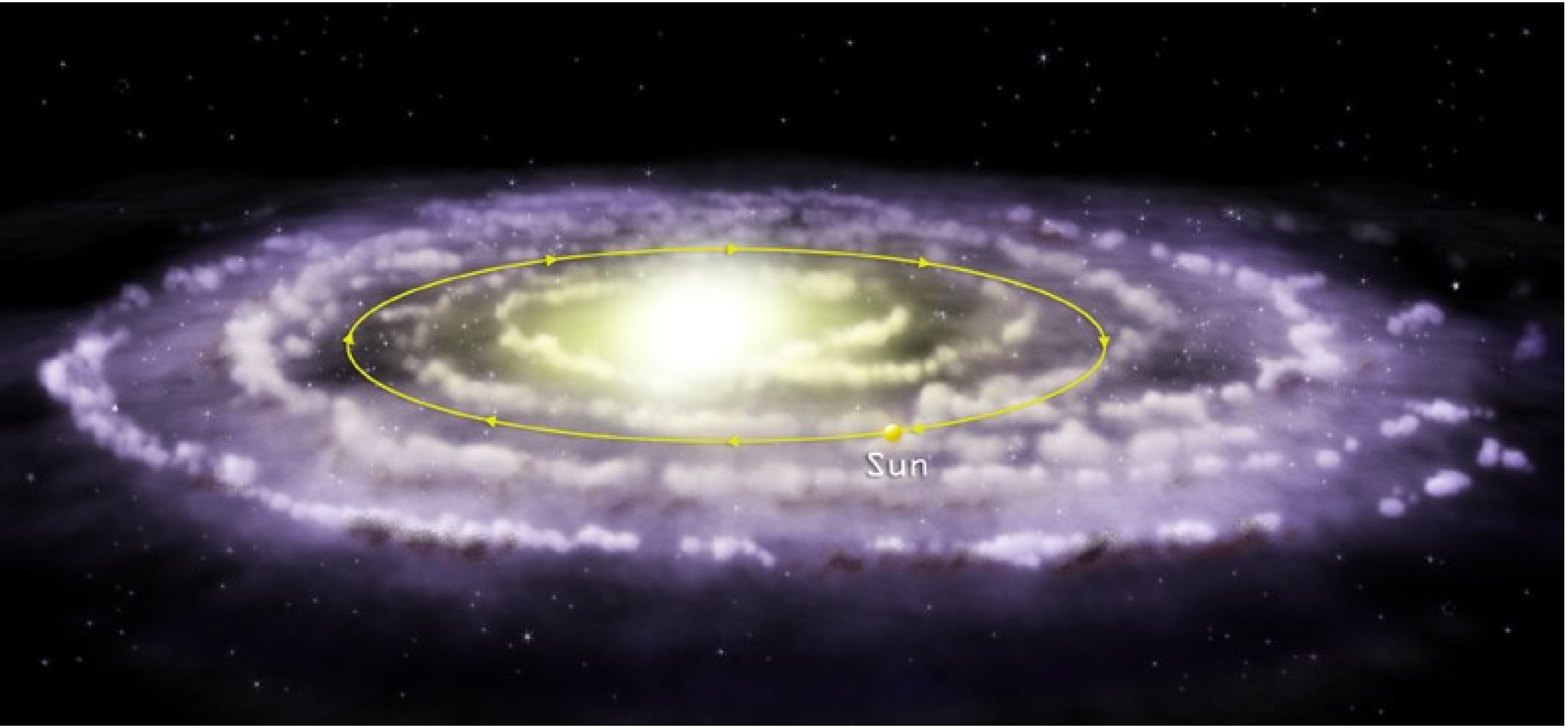
2θ is the angular displacement of an object
(with respect to the fixed stars)
when the Earth moves for half an orbit (6 months).

$$d = \frac{r_\odot}{\theta} = \frac{1 \text{ Astronomical Unit}}{\theta}$$

$$1 \text{ A.U.} = 1.495 \times 10^{13} \text{ cm}$$

Parsec = distance that corresponds to one arc-second

$$\text{parsec} = \frac{1 \text{ AU}}{1 \text{ sec arc}} = \frac{1.495 \times 10^{13} \text{ cm}}{4.8 \times 10^{-6}} \simeq 3.085 \times 10^{18} \text{ cm}$$



$$L(\text{Galactic Center}) \simeq 8.5\text{Kpc}$$

7.94 +- 0.42 Kpc
(new value)

Thickness 0.6 Kpc

Measurements Methods for the magnetic field in Astronomy:

- Zeeman effect
- Faraday Rotation
- Stellar Polarimetry
- Synchrotron Radiation

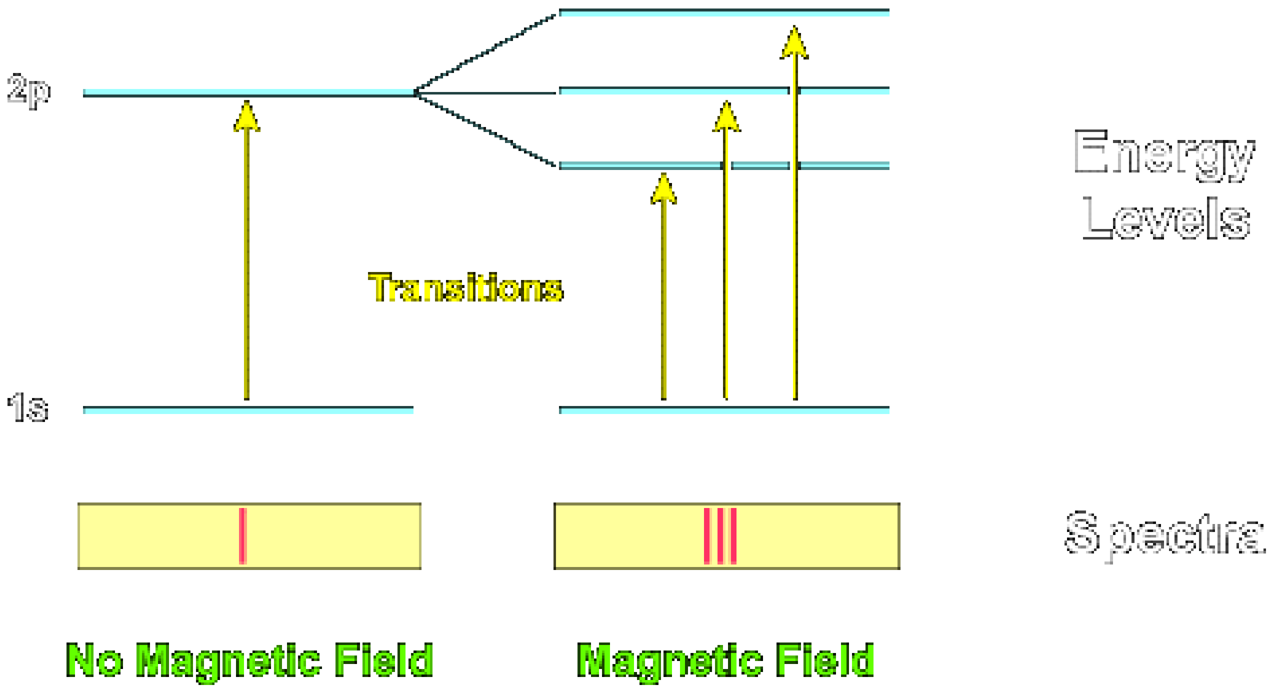
Zeeman effect

Splitting of emission lines proportional to B

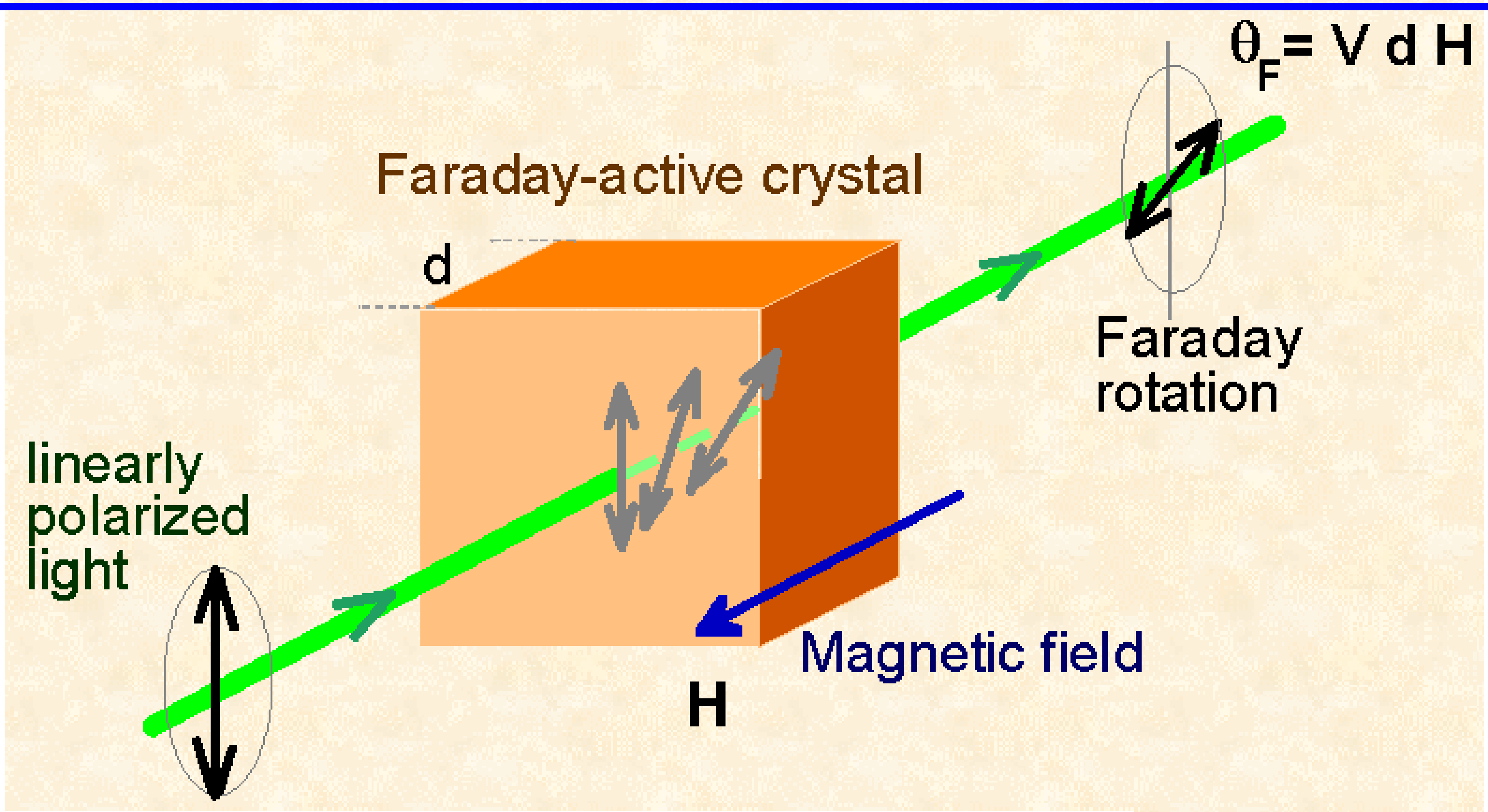
$$\Delta E = g \frac{e\hbar}{2m_e c} \; B \; j_z$$

First detection of B outside earth (1908): Sun spot

Split 2.8 Mhz/G for HI line



Faraday rotation and depolarization



$$\varphi = \frac{e^3 \lambda^2}{2\pi m_e^2 c^4} \int_0^{\ell} d\ell' \; n_e(\ell') \; B_{||}(\ell')$$

$= 0.81 \langle n_e B \rangle L(pc)\ rad/m^2$

Sensitive to parallel components and sign.
Only regular component.

Stellar Polarimetry :

Dust Grains are non spherical
the align orthogonally to the magnetic fiels

Absorb light mostly along their major axis
The light from an unpolarized source arrives prevalently polarized parallel to B

$P = K\ B\ \zeta\ \delta L/(N_h T_g T^{1/2})$

δL is the line of sight
T_g the grain temperature
T is the gas temperature
B the normal magnetic field
ζ is the grain density

Synchrotron Emission :

(Radio waves)
Emitted by electrons in a magnetic field
ν_{max} = 4 MHz E(GeV)^2 B(μG)
Photons are linearly polarized $p=(1-\gamma)/(7/3-\gamma)$
With γ spectral index of cosmic ray electrons

Emissivity $\varepsilon = N0\ \nu^{(\gamma+1)/2}\ B^{(\gamma-1)/2}$

Equipartion principle :

The energy densities of cosmic rays and magnetic field in the galaxy are comparable:
$W_{cr} \sim \rho v^2/2 \sim B^2/8\pi$
Reasonable at large scale

Indipendent measurement of cosmic ray density (local, γ-ray emission) in our galaxy and B field (synchrotron radiation)→
6 μG and 10 μG in inner galaxy that is consistent with equipartition principle

$$r = 1.08 \frac{E(10^{15}\ \mathrm{eV})}{Z\ B(\mathrm{microGauss})}\ \mathrm{parsec}$$

The Larmor Radius of the cosmic Rays in the galaxy is for most particles much smaller than the linear dimensions of the Galaxy (10^4 pc) or transverse (10^2 pc)

Motion is in the "DIFFUSIVE" regime

Cosmic Ray Diffusion